Is the growth of Rhododendron influenced by duration of snow cover or growing season length?

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by

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To my parents

Abstract

The dwarfing of trees along the elevation gradient in mountainous terrain has been attributed to adverse climatic conditions, but the effect of these conditions on tree growth rates have rarely been investigated. The aim of this research is to study the spatial variability of the height and of the annual shoot length of two *Rhododendron* species and to investigate its relation with the duration of snow cover and the length of the growing season. Tree height and annual shoot length were measured for two *Rhododendron* species (*Rhododendron campanulatum* and *R. campylocarpum*) along altitudinal gradients near the treeline in Sagarmatha National Park, Nepal. The annual shoot length did not significantly differ between N, E, S and W exposed branches of individual plants. Site exposition had a significant effect on variation of the annual shoot length between plants. Linear regression revealed significant declines of both tree height and annual shoot length with increasing elevation. MODIS time series were used to investigate whether snow cover duration (MOD10A1 daily data 2000 to 2007) and the length of the growing season (16- day NDVI composite of MOD13Q1, 2000 to 2008) could explain this decrease of annual shoot length. Annual shoot length did not relate to the number of days with more than 10% or more than 50% of snow cover. Savitzky-Golay, double logistic regression and asymmetric Gaussian functions however did not reveal significant relation between annual shoot length and length of the growing season. These results suggest that factors other than duration of snow cover and the length of the growing period influence the growth rates of these two *Rhododendron* species.

Keywords: Khumbu Himal; treeline; *Rhododendron* sp.; annual shoot length; fractional snow cover; growing season length, MODIS.

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1. Introduction

A reduction in tree size is commonly observed along altitudinal gradients in high altitude ecosystems. This reduction reaches a certain limit in which trees are no longer present and shrub forms of the same tree species or of new species dominate the landscape. Being the major vegetation component, different *Rhododendron* spp. represents this phenomenon, termed as treeline, in the East Himalaya mountain region.

Temperature decrease has been the most studied factor associated to the reduction in size and appearance of the treeline boundary (Körner, 1998; Körner & Paulsen, 2004). The interaction between this morphological change and other factors, such as snow cover permanence and length of the growing period, still remained largely unexplored. There is increasing scientific interest in investigating such interactions; mainly because of the possible effects that climate change might have on the structure and composition of mountain ecosystems (Grace *et al.*, 2002).

This research explores the spatial variability of growth in a mountain ecosystem and analyzes by means of remote sensing how it is related to the duration of snow cover and the growing period.

1.1. Background

1.1.1. The treeline boundary

At high elevations, trees give way to dwarf shrubs, forming a line, which is commonly termed as treeline[1] (Grace *et al.*, 2002). The treeline is not a sharp boundary; it is a transitional and sometimes very ragged zone. Ecological conditions change continuously with elevation, therefore the treeline represents a limit where this change is expressed by the replacement of dominant life forms by others and changes in plant communities' composition (Schickhoff, 2005).

The characteristics of the treeline differ at a global and local scale. Globally, the most important factor that determines treeline is heat deficiency (Körner, 1998; Gehrig-Fasel *et al.*, 2008) which leads to insufficient air and soil temperatures and shortens duration of the growing season, which in turn affects the survival of trees. However locally many factors combined determine the position and other characteristics of the treeline, such as extreme climatic events, snow and ice, soil properties, carbon balance, topography etc., therefore its study is extremely complex (Holtmeier & Broll, 2005).

Because of the above (Schickhoff, 2005) argued that it is difficult to find a common pattern that explains the structure, composition, appearance and position of treelines locally. Relations between topography and climate, which determine snow permanence, solar radiation, length of growing period, precipitation, ecology of the species, seed dispersal characteristics and anthropogenic disturbances interact to model this ecological boundary (Körner, 1998; Körner, 2003; Holtmeier & Broll, 2005).

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[1] In this work, the definition for treeline proposed by Korner (1998) is followed. He defines the treeline or forestline as a rough line that connects the uppermost patches of forest within a given an altitudinal gradient.

1.1.2. The Himalayan rhododendron forests at the treeline

In Nepal, the genus *Rhododendron* (*Ericaceae*) consists of 32 species, which are woody plants distributed throughout the montane and alpine zones (Noshiro & Suzuki, 2001; Bhattarai & Vetaas, 2003). The genus presents a number of tree and sub-tree like species, as well as shrubs (Noshiro & Suzuki, 2001). Some *Rhododendron* species have a wide altitudinal distribution range, while others cover a very restricted distribution (Vetaas, 2002).

Rhododendrons are a major component of high altitude vegetation especially in the East Himalaya Mountain Range (Vetaas, 2002). This area receives more influence of the tropical monsoon, moisture levels are higher, allowing the development of evergreen forests of rhododendrons at the uppermost forest limit (Shrestha, 1999). Rhododendrons are found not only at the treeline, different species are present in a broad range of elevations.

In the East Himalaya Mountain range, vegetation structure changes along the altitudinal gradient in a very characteristic way (Fig 1.), that is associated among other factors, to the exposure, rainfall, wind and the land use (Miehe, 1989). At lower elevations, in the montane zone, tree forms of Rhododendrons form the understory of *Betula utilis* forests, which develops in north facing slopes, and of *Abies spectabilis* forest, which prefer south facing slopes. As altitude increases, rhododendrons become the dominant group, along with *Juniperus sp. Betula* and *Abies*, tend to disappear and pure thickets of Rhododendrons form the canopy, creating a transition zone between the montane and alpine ecosystems. At higher elevations, in the lower limit of the alpine zone, shrubs forms of rhododendrons developed (Noshiro & Suzuki, 2001; Bhattarai & Vetaas, 2003; Mingyuan Fang *et al.*, 2004a)

Consequently, along the altitudinal gradient of the East Himalaya, *Rhododendron* species changed from developing in a dense forest to grow as isolated individuals of smaller size (Schickhoff, 2005). Rhododendrons species that have a wide altitudinal range are exposed to a broad gradient of environmental conditions and present the above mention vegetation pattern (Vetaas, 2002). Beside the morphological changes, along the elevation gradient, there is also a change in species composition (Noshiro & Suzuki, 2001). However some species developed as trees in the montane forest and gradually change into shrubs or dwarf forms until they disappear in the upper alpine zone (Fig 1).

This characteristic morphological variation in rhododendron trees, make them an appropriate group for the study of growth along the altitudinal gradient. As well as those interactions with the environmental factors that might be determining growth and causing the observed morphological variation.

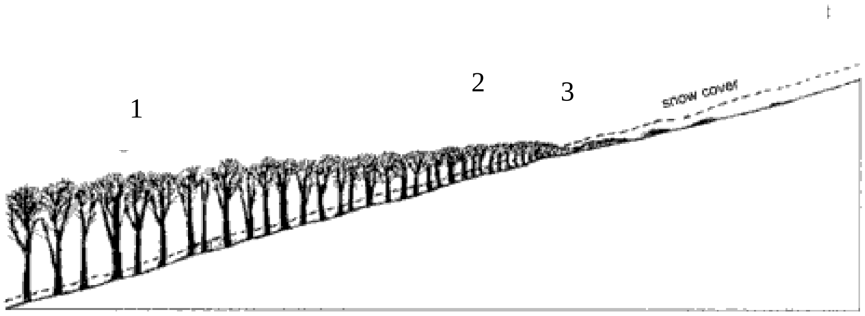


Fig. 1. Diagram of vegetation change along the treeline. *Betula utilis* or *Abies spectabilis* forest with *Rhdodendron* understory, montane zone (1), Pure *Rhododendron* forest near treeline(2), Shrubs at the vegetation, alpinezone (3) (adapted from Pollmann &Hildebrand(2005)).

1.1.3. Characteristics of growth at high altitudes

High altitude evergreen vegetation, such as *Rhododendron* forests, present cycles, alternating periods of growth and winter dormancy (Körner, 2003). The period of growth normally corresponds with the melting of the snow, time in which the upper soil horizons thaw. The winter dormancy starts when freezing temperatures return in the fall. Evergreen vegetation goes through a period of dormancy, because water and nutrient availability in the soil is restricted due to freezing temperatures. During this period growth processes are suspended, metabolic activity is reduced and resistance to frost and desiccation is enhanced (Kimball et al., 2004).

Even though the beginning of growing period occurs synchronized with snow melting, snowmelt does not necessarily trigger the beginning of the growing period. In fact, plants do not start producing new tissues until the day light last the adequate amount of time (Tranquillini, 1964). Photoperiodism, is a weather independent control, but once a certain threshold photoperiod is passed, temperature and snow permanence determines the growing progress (Körner, 2003). The end of the growing season is coupled to the photoperiod in combination with temperature, since low temperatures affect photosynthesis, water availability, gas exchange and stomatal closure in plants (Sakai & Malla, 1981; Gehrig-Fasel *et al.*, 2008).

Since several factors influence the length, start and end of the growing period, there is variation between ecosystems (Churkina *et al.*, 2005). Latitude and elevation play a partial role in determining growing season length (Kimball *et al.*, 2004). Topography and temperature are also important factors because they influence the timing of snow melt (Körner & Paulsen, 2004; Linderholm, 2006). In addition water availability, which is a factor related with temperature, is also important in mountain ecosystems. Water in the soil becomes available after melting temperatures has been reached. Afterwards, plants will be able to use water and nutrients present in the soil (Kimball *et al.*, 2004).

Growing season also varies between vegetation types and can be a determinant factor of vegetation distribution. In fact, evergreen vegetation have longer growing periods than deciduous (Griffis *et al.*, 2003). Vegetation distribution patterns could be linked to biomass production, which is directly related to the length of the growing period (Kimball *et al.*, 2004; Bader *et al.*, 2008).

Consequently treeline characteristics and position can be explained by differences in biomass production (Kimball *et al.*, 2004). Species and life forms might be able to develop only above a certain threshold of possible growing days. Therefore, the timing and duration in which plants can growth can be influencing the altitudinal distribution of vegetation.

In the case of Rhododendron, shortly after winter dormancy is suspended; the apical meristem becomes active again and flowering takes place. Depending on the altitude the time of blooming varied (de Milleville, 2002). After blooming, biomass production begins and shoots grow for a whole period, tree height increase and branches elongate (Chudamani pers. comm.). Branches will elongate until freezing temperatures return in fall and plants become dormant once more (Wilson *et al.*, 1987).

In conclusion, the process of the start and the end of the growth period is complex as it is influenced by many ecological aspects of high mountain systems. Due to the harsh environmental conditions, plants have developed many controls to regulate the starting and ending of the period for energy investment on photosynthetic tissue. In turn, this regulation has also determined many of the characteristics of high mountain ecosystems, such as the growth of the vegetation developing at the treeline.

1.1.4. Application of satellite time series to the study of growth

Availability of satellite data offers new possibilities of studying the growing period of different ecosystems at a landscape level. Satellite time series have been used to analyzed the variation of environmental parameters, and vegetation response to such variations, providing new information for monitoring of high altitude ecosystems (Grace *et al.*, 2002; Pettorelli *et al.*, 2005). A good example of such monitoring has been its application on the study of possible effects of climate change on the phenology of high mountain ecosystems (Karlsen *et al.*, 2008).

Probably due to the interest in climate change impacts, recently many studies have been done using time series. These studies applied different sensors and algorithms in order to estimate growing season parameters (Jonsson & Eklundh, 2002; Suzuki *et al.*, 2003; Zhang *et al.*, 2003; Kimball *et al.*, 2004; Delbart *et al.*, 2005; Pettorelli *et al.*, 2005; Yu *et al.*, 2005; Beck *et al.*, 2006; Delbart *et al.*, 2006; Linderholm, 2006; Beck *et al.*, 2007; Fisher & Mustard, 2007; Karlsen *et al.*, 2008). Most of the research on phenological cycles is based on monitoring vegetation change, such as the senescence and vegetation green-up. These studies focus on the observable effects of the growing period.

However, since growth is control by multiple factors, growth studies can also be performed by analyzing variations of environmental factors, such as snow permanence, and relating it to growth.

Snow permanence will provide information possible causes of the observed growth, while the study of vegetation change will give details on growth consequences.

1.1.4.1. Snow Cover Permanence and the Normalized Difference Snow Index

In high mountain ecosystems and alpine regions, snow cover determines many biological processes. Snow permanence affects the length of the growth period, the flowering timing and the process of seedling establishment (Körner, 2003). Species composition and vegetation distribution is also influenced by the duration of snow cover, which is related directly to topography (Tappeiner *et al.*, 2001). Due to its influential effect on biological, hydrological and ecological processes, effort have been invested on developing accurate ways for mapping snow cover and study its duration in the last decade (Hall & Riggs, 2007).

Snow can be studied through satellite time series, because of its intense contrasts with other natural surfaces, except clouds (Gupta *et al.*, 2005). The reflectance of fresh snow is high, but it varies somewhat according to grain size, solar elevation angle, liquid water content, surface roughness etc. (Hall *et al.*, 2002) Clouds and snow can be distinguished from each other, as clouds have high reflectance in visible and NIR and snow decreases reflectance in shortwave infrared wavelengths (Hall *et al.*, 1998).

Snow mapping is based on the Normalized Differential Snow Index (NDSI), which is an algorithm that allows estimating how much snow is actually present in a pixel. The NDSI is defined as the difference of reflectance observed in a visible band, around 0.55µm and short wave infrared (1.640 µm) divided by the sum of reflectance of both bands. In MODIS this is defined as:

NDSI = (band 4 - band 6)/ (band 4 + band 6) (Hall & Riggs, 2007).

To obtain the fraction of snow cover (FSC) in a pixel, regression equations were derived based on the calculated NDSI and the snow cover present on Landsat ETM+ (Salomonson & Appel, 2004). The resulting FSC data set from MODIS based on regression equations was released in 2006.

Significant progress has been made on the study of snow through remote sensing, but application of snow mapping, remains quite limited especially in forested areas. Even though snow can be distinguished from other natural surfaces, in dense forest canopies its mapping becomes limited. Normally snow does not stay in the tree canopies, due to sublimation, for the whole winter(Delbart *et al.*, 2006). Snow from the ground will not be visible from above, except with radar remote sensing. As a result, dense forested areas will never be completely snow-covered (Hall *et al.*, 1998). Models have been developed to correct for this in order to obtain the percentage of snow cover in forested areas.

These models are based on the fact that snow has higher reflectance in the visible wavelengths than leaves and trees. Therefore when there is snow the reflectance on the visible part will increased with respect to the near infrared reflectance. As a consequence the NDVI values will drop. A combination of NDVI and NDSI is used to improve the mapping of snow in dense forest (Hall *et al.*, 1998; Hall *et al.*, 2002; Hall & Riggs, 2007).

In conclusion, there are still many challenges in the mapping of snow in relation to forested areas. However, time series of snow cover, does provide an interesting indication on the variation of this climatic parameter and an opportunity to study vegetation growth response to this variation.

1.1.4.2. Growing season length and the Normalized Difference Vegetation Index

Vegetation indexes have been designed for the monitoring of vegetation conditions. Nowadays, most of the monitoring of large scale vegetation dynamics is based on NDVI time series (Beck *et al.*, 2007). In many recent ecological studies, NDVI time series have been successfully used to increase the knowledge on direct and indirect effects of environmental change in vegetation (Pettorelli *et al.*, 2005).

The NDVI is the most commonly used parameter in growing season length studies, because it provides a measurement of the vegetation state (Cihlar *et al.*, 1991). Changes in NDVI datasets, reflected seasonal changes in the greenness of the vegetation throughout the year, that can be related to the start and end of the growing season (Yu *et al.*, 2005).

The NDVI quantifies the contrast between the red and infrared reflectance, by calculating the ratio of the red and near-infrared surface reflectance:

$NDVI=(\rho NIR - \rho Red)/ (\rho NIR + \rho Red)$ (Tucker, 1979).

This is based on the concept that higher amounts of chlorophyll and other pigments (which are abundant on green vegetation) will absorb red radiation, while increasing canopy complexity will scatter infrared radiation, therefore when vegetation is greener NDVI value increases, varying from -1 to 1.

The study of vegetation phenology has been based on different NDVI datasets, which have different spatial and temporal resolutions. Among this data sets are:

i. Long-term National Oceanic and Atmospheric Administration–Advanced Very High Resolution Radiometer (NOAA AVHRR) time-series extends from 1981 to the present (datasets include PAL,GVI and GIMMS). Even though its low resolution (8–16 km resolution) it has been used in a high amount of studies (Cihlar *et al.*, 1991; Jönsson & Eklundh, 2004; Delbart *et al.*, 2006).

ii. Short-term NDVI time-series includes the Moderate Resolution Imaging Spectroradiometer (MODIS–TERRA) data set (250–1000 m resolution) extending from 2000 to the present, and the Satellite Pour l’Observation de la Terre–Vegetation (SPOT–VGT) data (up to a few meters resolution) extending from 1998 to the present.

Recently many studies have used MODIS-NDVI composites to determine the length of the growing season (Zhang *et al.*, 2003; Yu *et al.*, 2005; Beck *et al.*, 2006; Beck *et al.*, 2007; Fisher & Mustard, 2007; Karlsen *et al.*, 2008). Most of them were done on larger areas of Europe and North America. These studies applied field phenological observations to associate the NDVI to the sprout or the senescence of the leaves and modelled the time series through different fitting functions to smooth the NDVI data.

As a final point, it is important to remark one limitation of the application remote sensing to length of the growing season studies. This type of studies must always be limited to establish a relation between a species or a few species to a large area, which can result on biased association between many species phenological events and the satellite data (Schwartz, 1999).

1.2. Research Problem

Low temperatures have been studied as the main explanatory variable of the growth variability observed along the treeline. The effects of the conditions associated to the growth variability present in treeline species such as *Rhododendron* have rarely been investigated. Information is lacking on the spatial variability of these conditions that might be influencing the dwarfing of trees.

There is increasing scientific interest on studying the treeline; mainly because of the possible effects that climate change might have on this ecological boundary. Among the possible effects is that change in climatic conditions will affect the growth of the species that developed along the treeline. Through the study of the length of the growing season and the snow cover permanence, the conditions that cause the growth variability the species that developed along the treeline can be better understand. So the real possibility of changes in growth in high altitude ecosystems could be contextualized.

Time series provide valuable information to perform such studies to improve the understanding of growth along the treeline. The combination of field measurements of tree growth with remote sensing data on snow cover permanence and vegetation change can provide important insights on the factors that direct Rhododendron growth rates at high altitudes. Up to now this type of the studies have been not been performed.

1.3. Research Objectives

1.3.1. General Objective

The aim of this research is to study the spatial variability of the height and of the annual shoot length of two *Rhododendron* species and to investigate its relation with the duration of snow cover and the length of the growing season.

1.3.2. Specific Objectives

The general objective will be achieved by the following specific objectives:

1. To investigate the spatial variability of the annual shoot growth of Rhododendron species due to topographical variables (altitude and aspect).

2. To study snow permanence in the area and its relation to the annual shoot growth.

3. To study the length of the growing season derived from NDVI time series using different fitting functions and its relation to annual shoot length.

1.4. Research Hypothesis

1- Ho There is no relation between tree height of rhododendrons and the altitude and aspect.
1- Ha: There is a relation between tree height of rhododendrons and the altitude and aspect.

2- Ho: There is no relation between annual shoot growth of rhododendrons and the altitude and aspect.
2- Ha: There is a relation between annual shoot growth of rhododendrons and the altitude and aspect.

3-Ho: There is no relation between the snow cover presence and the annual shoot length of rhododendrons.
3-Ha: There is a relation between the snow cover presence and the annual shoot length of rhododendrons.

4-Ho: There is no relation between the length of the growing season and the annual shoot length of rhododendrons
4-Ha: There is a relation between the length of the growing season and the annual shoot length of rhododendrons.

1.5. Research Questions

1. What is the relation between altitude and aspect and the height of *Rhododendron* species?

2. What is the relation between altitude and aspect and the annual shoot length of *Rhododendron* species?

3. What is the relation between the amount of days with snow cover and the annual shoot length growth of *Rhododendron*?

4. What is the relation between the annual shoot growth and the length of the growing season as determined by the fitting functions?

2. Methods and Materials

2.1. Study area description

The study area comprehends an altitudinal gradient found in the vicinity of Tengboche (27° 50` N, 86 46` E), in the Imja River Valley in the Sagarmatha National Park, in the Khumbu Himal region (Fig 2). This area was chosen for two main reasons. The first reason is because it has large extensions of rhododendron forests. Secondly, the area offers the possibility to observe the transition from dense forest to more shrubby life forms as the altitude increases, hence it captures the treeline boundary. The treeline in this area is located at aprox. 3900 masl (Sakai & Malla, 1981; Schickhoff, 2005) although other author's report it at 3800 masl (Dobremez, 1976) in (Schickhoff, 2005) .

Rhododendron campanulatum and *R. campylocarpum* are the two main *Rhododendron* tree species found in the area, while *R. anthopogon* is the main shrub-like specie. Other tree species that are also found in forested areas at this elevations are *Betula utilis*, *Abies spectabilis*, and *Juniperus recurva* on south facing slopes .

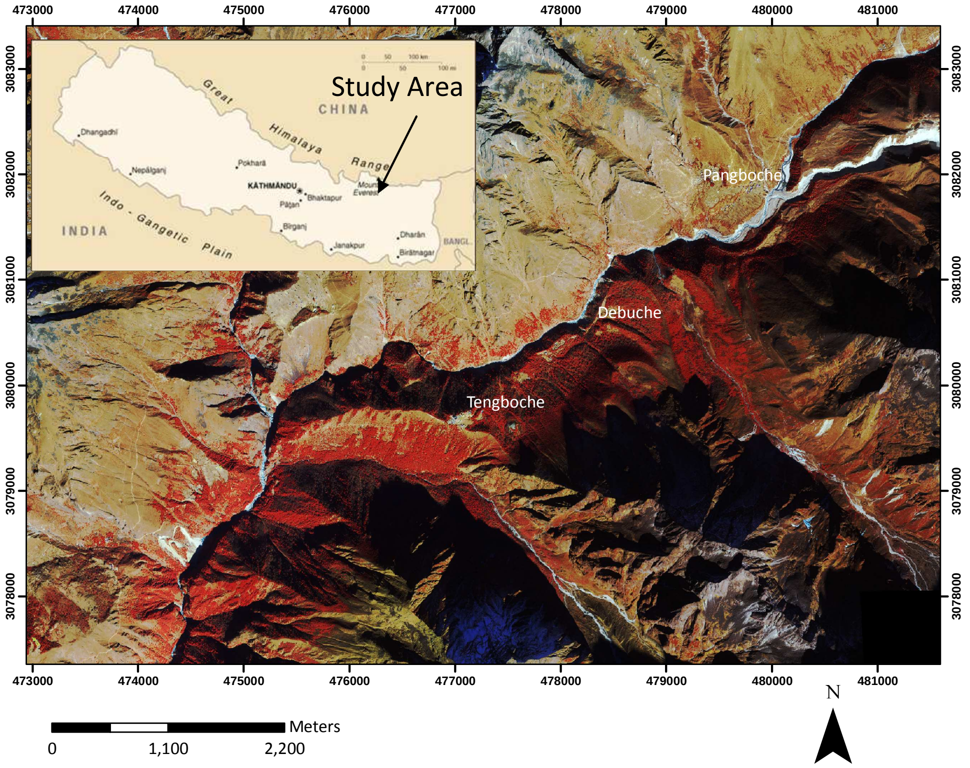


Fig. 2. Ikonos image (2003 431) subset of the study area showing the main settlements, Sagarmatha National Park, Solu Khumbu region.

The mean annual precipitation is 1032 mma^{-1} , most of the precipitation occurs during monsoon season from June to September. The coldest month presents a mean annual temperature of -3.8° C, while the warmest month mean annual temperature is 9.4 °C (Schickhoff, 2005).

In this area, south facing slopes are exposed to the influence of the monsoon while the north facing slopes will present more arid conditions due to the Föhn effect (Sakai & Malla, 1981; Miehe, 1989; Schickhoff, 2005). In addition south facing slopes receive higher irradiation in spring, fall and winter, and therefore less duration of snow cover (Miehe, 1989).

2.2. Species description

In this research two characteristic Himalayan Rhododendron species were sampled:

Rhododendron campanulatum D. Don: is a small tree, that can reach up to 6 meter, but its normal height is between 1 to 5 m (Mingyuan Fang *et al.*, 2004a). This specie is characterized by its bell-shaped flower. It grows from 2800- 4400 masl, its mean altitude is 3700 (de Milleville, 2002; Vetaas, 2002). It can forms dense, pure forest around 3800 masl and can also be found in combination with *R. campylocarpum*. In very steep areas, these trees tend to produce branches parallel to the ground (de Milleville, 2002). It is one of the few species Rhododendron that also grows in the Central and West Himalaya (Vetaas, 2002).

R. campylocarpum Hook. f.: is a small tree, that develop up to 4 m tall. It grows in scattered forests or shrubberies, between 3300 to 3900 masl (de Milleville, 2002) . It presents pubescence on the adaxial leaf and on the petioles, which are its diagnostic characteristic (Mingyuan Fang *et al.*, 2004b).

2.3. Field data collection

2.3.1. Sampling methodology

In the study area, four transects were done. The transects covered an altitudinal gradient from 3750 to 4050 masl. Along each transect, areas of aprox. 200 X 200 m which its main vegetation component was *Rhododendron* forests were identified. In these areas, 20 X 20 m plots were established. Following the altitudinal gradient, plots were established every 50 meter in altitude. However due to the difficult topography, in some cases this was not possible, so samples were taken in the nearest site where the 50 meter difference was reached.

A total of 34 plots were made in the field. These plots were established with the purpose to take some of the measurements (see below collected data), as the real sampling unit in this case was the individual tree. In each of these plots 1 to 4 individual trees from the above mentioned species were randomly selected.

2.3.2. Collected data

For every plot the following data was described:

a. Location: the location was recorded by a GPS receiver at the center of the plot.
b. Altitude: altitude was estimated at the center using an altimeter.
c. Slope percentage was calculated using a clinometer at the center of the plot.
d. Aspect: the aspect of the plot was described qualitative. Based on the position of the sun, slopes were categorized as north, north-west, west etc. facing. This classification was later verified as the points were plotted on the map.
e. Main vegetation type: by visual inspection, a general description of the main vegetation observed in the plot was done. The percentage of the two *Rhododendron* spp. of interest and other tree spp. observed inside the plot was recorded.

Besides the above mentioned data, information on the growth of the trees was collected. First, tree height was estimated, using the height of one of the researchers as reference. Even though the lack of precision of this method, it was use for practical reasons.

Second, data on annual shoot growth or annual shoot length (ASL) was recorded as follows. In total, 56 trees of *R. campanulatum* and 17 trees of *R. campylocarpum* were sampled. In each tree from 1 to 4 branches were measured. The branches were selected according to the four main directions. It was not possible to always sample branches in all four directions due to the slope, but in the majority of the trees we managed.

On each branch the annual shoot length was measured. The annual shoot length was defined as the distance (cm) from the scar left by the whorl of leaves produced in the apical meristem of one year to the next scar left by the whorl of leaves produced the following year (Fig 3). Since leaves are produced each growing season, it is possible to associate the annual shoot length with a particular year. This study assumes that the annual shoot length represents the growth of a consecutive growing period, before the meristem become dormant again.

As this study was undertaken in late summer 2008, the annual shoot length from 2007 backwards was recorded. A metal measuring tape which has a measurement error of 0.5 mm was used to measure the annual shoot length. A total of 158 branches for *R. campanulatum* were measured and 56 branches for *R. campylocarpum*.

It was possible to measure the annual shoot length for 10 years in many of the branches, after that the scars were not visible anymore. Since the available satellite data starts in 2001, only data from 2001 to 2007 was used for the rest of the analysis.

In addition to the annual shoot length, the number of branches produced in each shoot was counted. The number of branches varied from 0 to 4 per node. Since older shoots could have the same amount of branches as younger ones, no define pattern was observed in the number of branches per shoot. Therefore no posterior analysis was done with the data on the number of branches. However it is important to mention because it might be useful for posterior studies on the subject.

Fig. 3. Example of annual shoot length measurement in *R. campanulatum*

2.4. Data Analysis

2.4.1. Analysis within plants

Since the growth of a branch could possibly be influenced by its exposition towards the sun and this could bias the posterior analysis, first the effect of the exposition within the tree on the annual shoot length was analyzed. An ANOVA on annual shoot length (normalized per individual tree, to remove differences between trees) was performed, to compare if there was a significant effect of the exposition on the length of the shoots for *R. campanulatum*. Only *R. campanulatum* individuals which have measurements of annual shoot length on the four main directions were used in this analysis. The ANOVA revealed that there is no significant difference in the mean annual shoot length from the year 2001 to 2007 between the four main directions (Fig.4, $F_{(3,106)} = 0.556$, $p=0.646$).

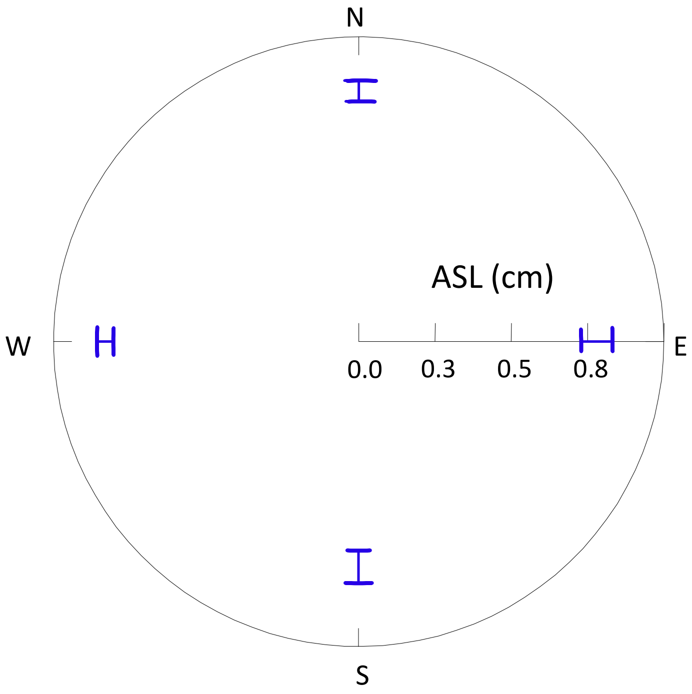


Fig. 4. Normalized mean annual shoot length (from 2001-2007) ± SE by aspect for *R.campanulatum.*

It was concluded that the exposition of the branch did not significantly influence the annual shoot growth. Hence the data for each plant could be average and the averaged annual shoot length per plant was used for the rest of the analysis.

2.4.2. Analysis spatial variability of growth in *Rhododendron*

In this study measurements of tree height and annual shoot length were used as surrogates of growth of rhododendron species at the treeline. The variability in the growth of rhododendron trees and the topographical variables altitude and aspect were analyzed as follows.

First, to analyze the relation with the aspect only the data for *R. campanulatum* was used, because it was the only species collected on sufficient sites with different aspects. An ANOVA was applied to test for: a. differences in tree height between aspects and b. differences in mean annual shoot length per tree between aspects. For proper interpretation of the data collection it should be noted that most of the plants were recorded on north, east and west facing slopes, with fewer samples from south facing slopes, were *Rhododendron* was rare.

Second, linear regression analysis were done to test the relation between the altitude and a. Height of *R. campanulatum* and *R. campylocarpum* b. Each year annual shoot length of both species and the altitude.

A two sample t-test was applied to the slopes obtained in the linear regression analysis, to analyze whether the reduction in growth rates with the altitude differed between the two species. The slopes obtained from regressing height, mean annual shoot length and each year annual shoot length vrs the altitude were tested.

All this analysis provided an indication of the spatial variability of growth based on height and the annual shoot length and the influence that altitude and slope have on the growth of the *Rhododendron* species.

2.4.3. Snow permanence and annual shoot length

To understand the relation that snow cover permanence could have on the growth of *Rhododendron* species time series on snow cover were used. Time series were chosen because weather stations of the area do not record information on snow permanence or snow depth. The following MODIS product was used for the analysis.

2.4.3.1. MOD10A1: Fractional Snow Cover Daily Tile

MOD10A1 is part of MODIS/Terra snow products. It has global coverage and daily spatial resolution. Its processing level is 3. Each tile is a 1200 km X 1200 km scene with a spatial resolution of 500 m. This product consists of four scientific data sets (SDS) : snow cover, snow albdedo, fractional snow cover (FSC) and Quality Assessment (QA) data, all of them in compressed Hierarchical Data Format-Earth Observing System (HDF-EOS) format and in sinusoidal projection (Hall *et al.*, 2002; Hall & Riggs, 2007).

The FSC refers to the percentage of snow present in a pixel, therefore it provides more information than the snow cover data set, which just tells if there is snow present in a pixel or not. It is a new SDS released with collection 5 in December 2006 (Riggs *et al.*, 2006). According to (Hall & Riggs, 2007), snow cover products daily tile have an average accuracy of 93%, (validated stage 2), which means that data is ready to use for scientific purposes, since its accuracy has been assessed through wide distribution of ground truth locations for a long time period. A summary of the data quality of the pixels used in the analysis is given in Appendix B.

2.4.3.2. Snow dataset processing and determination of snow permanence

MOD10A1 images FSC dataset for the period of 1 January until the 31 May, and from 1 October until the 31 December from 2001 to 2007, tile h25v6, collection 5 were used (Hall, 2006, updated daily.). This images were subset to the study area, reprojected to Geographic Coordinates WGS84, and resample by the nearest neighbour method; using the Modis Reprojection Tool (MRT tool) (Dwyer & Schmidt, 2006; NASA, 2009).

The subsetting was done using the following coordinates: UL: 27.86, 86.76; UR: 27.86, 86.79; LL: 27.82, 86.76 and LR: 27.82, 86.79. After the images were into the proper coordinate system, the extraction of the pixel values where the sample points were located was performed. Value extraction was done using Envi 4.5 + IDL.

A total of 240 days per year for 5 pixels where the samples where located was analyzed for snow cover (pixel coordinates are given in Appendix A). In the FSC dataset there were many days reported as No data (values 250,255) (Hall, 2006, updated daily.), therefore the calculations where made based on the percentage of reported days. An ANOVA was done to test if the number of reported days differs significantly between years. The amount of reported days did not differ significantly between pixels of different years ($F_{(4,30)} = 0.736$, $p = 0.574$). However, year 2004 and 2005 did have higher incidence of no data days, which could be affecting the results.

Afterwards, the data was categorized into two sets: a. days with an FSC >10% (wide-ranging snow cover percentage) and b. FSC > 50% (high snow cover percentage). The percentage of reported days with more than 10 % (wide-ranging) and 50 % (high snow cover) was determined. The reason behind this division was to study the possible effect that higher levels of snow cover (FSC > 50%) might have on the annual shoot length.

The average altitude per pixel was calculated and used to study if there was a trend in the amount of snow cover observed in each year. The average altitude was based on 10 meter resolution DEM, 20 random points were extracted from each pixel and the mean of the obtained values was calculated. Also the average annual shoot length of the samples found in each pixel was calculated.

To test for differences in the FSC between the years ANOVAs were used. A regression analysis was done between the mean annual shoot length of the samples present in each pixel and the percentage of reported days in which FSC was more than 10% and more than 50 %.

2.4.4. Growing season length and annual shoot length

To study how the length of the annual shoots was related to the growing season, first the duration of the growing season was modelled. NDVI 16-day composite images were process and use as input for the TIMESAT 2.3 program (Jönsson & Eklundh, 2004), which was use to estimate the growing season length.

2.4.4.1. MOD13Q1: Normalized Vegetation Index 16-day composite

MOD13Q1 is part of MODIS/Terra land products (Huete et al., 2002). It has a global coverage and it has been processed to level 3. Each tile is a 1200 km X 1200 km scene with a spatial resolution of 250 m. This product consists of twelve scientific data sets including a pixel reliability layer and a

Quality Assessment (QA) data, all of them compressed HDF-EOS format and in sinusoidal projection (USGS, 2008).

The 16-day composites are made by the Maximum Value Compositing Technique, in which the observation closest to the nadir, that is cloud free and has the highest NDVI value for a predefined period is selected to represent the whole period (Holben, 1986). In this way the increasing effect on the NDVI due to measures taken in oblique angles is eliminated. Also the images are corrected for molecular scattering, aerosols and ozone absorption; and are masked for cloud-shadows, clouds and water (Vermote *et al.*, 2002).

2.4.4.2. NDVI dataset processing and determination of the growing season

Images from MOD13Q1 data collection 5, tile h25v6, covering the period from 2001 to 2008 where used. Images were subset to the following coordinates: UL: 27.86, 86.7; UR: 27.86, 86.79; LL: 27.82, 86.76 and LR: 27.82, 86.79. The images where reprojected to geographic coordinates WGS84 and resample by nearest neighbour method, using the MRT tool (Dwyer & Schmidt, 2006; NASA, 2009).

The growing season was determined for eleven pixels (Appendix D), which correspond to sample points for *R.campanulatum*, using TIMESAT 2.3 software package. TIMESAT is a set of programs designed to analyze satellite data time series. Timesatimage is one of these programs, which fits functions to the time-series based on images instead of text files. It uses three different least square methods to fit the curves and to extract seasonal parameters out of the time series (Jonsson & Eklundh, 2002; Jönsson & Eklundh, 2004). These methods include a Savitzky Golay filter type, which is a local polynomial function, Asymmetric-Gauss and Double-Logistic method.

Timesatimage was run in MATLAB R2008a. In order to run it, each year should have the same number of images. Some years, 2002 and 2006, did not presented a complete set of 23 images. Therefore the missing values were replaced by the previous or image, in the case that only one image was missing, or by the previous and posterior image if two images were missing. Appendix C gives detailed information on the missing data. Even though that might lead to some error in the determination of the growing season length, it was a better option than to decrease the number of observations per year, in order to get the same number of images, which will reduce the available data considerably.

In addition, pixel reliability data set was used to check for pixel quality. Data classified as non-useful pixels were identified for each year, most of the time these pixels correspond with monsoon season. Test runs were made with the complete time-series and with time-series without the non-useful data. However eliminating unreliable data from the time series produced unrealistic results. Since TIMESAT programs pre-processed the data to remove outliers (values that are consider extremely different from the surrounding values), and non-useful data was classified as outlier by the program, it was decided to use the complete time series for further analysis. Detailed information on data quality is given in (Appendix E, F &G)

The subset and reprojected images were converted to flat binary files, using Envi 4.5 software to generate the input files. The following input parameters where used to process the time series:

a. Data Valid range (minimum and maximum value of the data to be process): -10000, +10000
b. Data cut offs or spikes (value above which the assign weight will be 0): 1.5
c. Number of seasons: 1
d. Number of fitting steps: 3
e. Strength of adaptation: 2
f. Processing methods: a. Savistzky Golay (SG), with window sizes with a value of 4, 5, 6 for each fitting step b. Assymmetric Gauss (AG) c. Double Logistic (DL)
g. Percentage of decrease of the seasonal amplitude (this parameter defines the threshold for starting and ending the growing season): 25

To test if the growing season length, estimated by the three fitting methods differs, between years ANOVA analysis were done. Finally, to determine the association between the IND and the growing season length, as determined by the three fitting methods, linear regression analyses were applied.

2.4.5. Annual Shoot Length Growth Model

Several general linear models to estimate the annual shoot length of *R. campanulatum* were constructed by combining altitude, annual shoot's age, the interaction between age and altitude with a. FSC>10 b. FSC> 50 c. growing season length by SG d. growing season length by AG e. growing season length by DL. The model that explained best the observed annual shoot length was chosen. In addition the correlation between the above mention variables and the altitude was calculated to understand the degree of dependence between snow cover vs. altitude and growing season vs. altitude.

3. Results

3.1. Analysis of the spatial variability of growth

3.1.1. Sample description

R. campylocarpum samples were obtained in a smaller distribution range, from aprox.3850-3950 masl, while *R. campanulatum* trees were sampled from 3750 - 4050 masl. Fig. 5 shows the median values for both species by the age of the shoots. Although there is variability in the samples as shown in Fig.5, in most of the cases younger shoots present smaller annual shoot length than older ones, for both species.

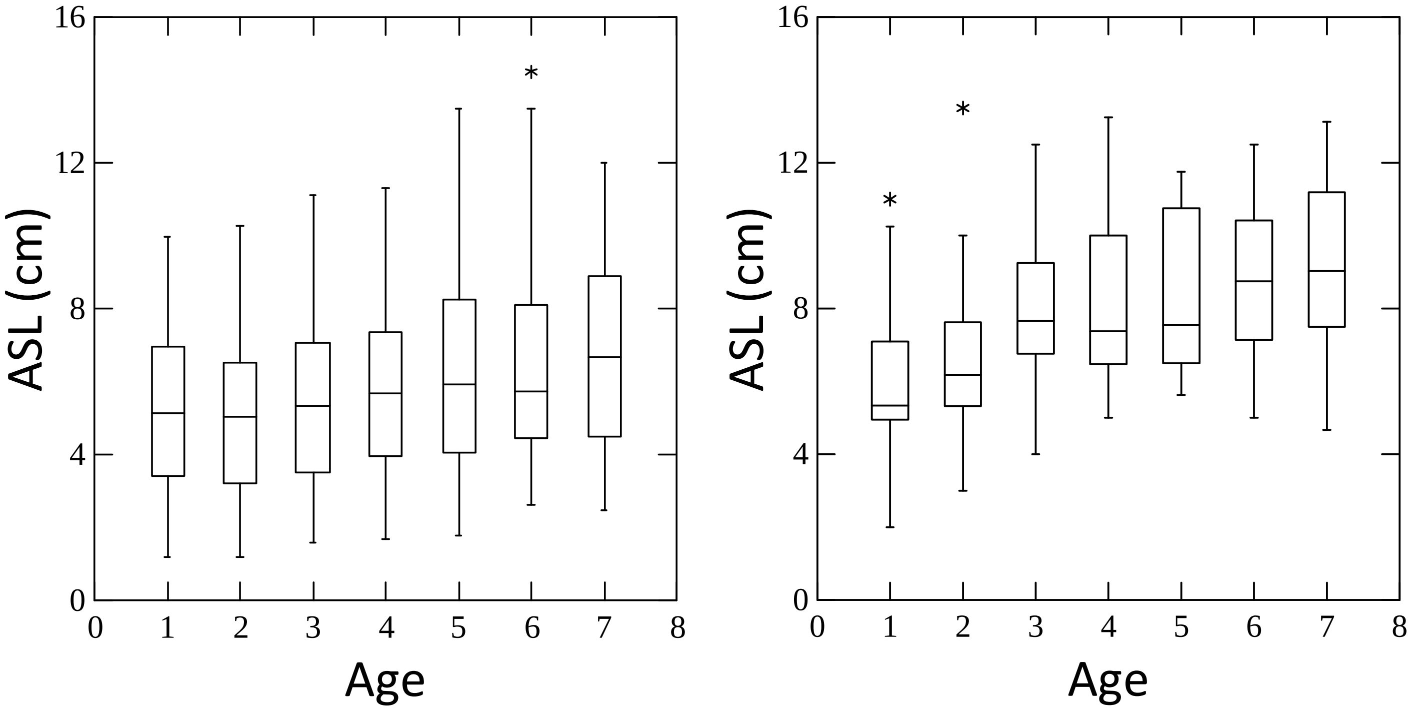


Fig. 5. Median annual shoot length by shoot age of the sampled rhododendron trees a) *R. campanulatum* b) *R. campylocarpum*

3.1.2. Influence of aspect in growth

The aspect is related to the amount of radiation that is received by the vegetation. Therefore the height and the annual shoot length were analyzed according to it. The data was grouped into the four main directions, considering north as 0 °degrees. There are differences in the tree height depending on the slope ($F_{(3,31)}$= 7.237, p= 0.001). Higher trees were found on north facing slopes, while the shortest trees where located in east facing slopes (Fig. 6. a).
The analysis of the mean annual shoot length for the years (2001-2007) revealed a different pattern. Trees located in west facing slopes presented the longest mean annual shoot length, while trees growing in the east had the shortest annual shoot length (Fig. 6b), ($F_{(3,52)}$= 8.51, p= 0.000).

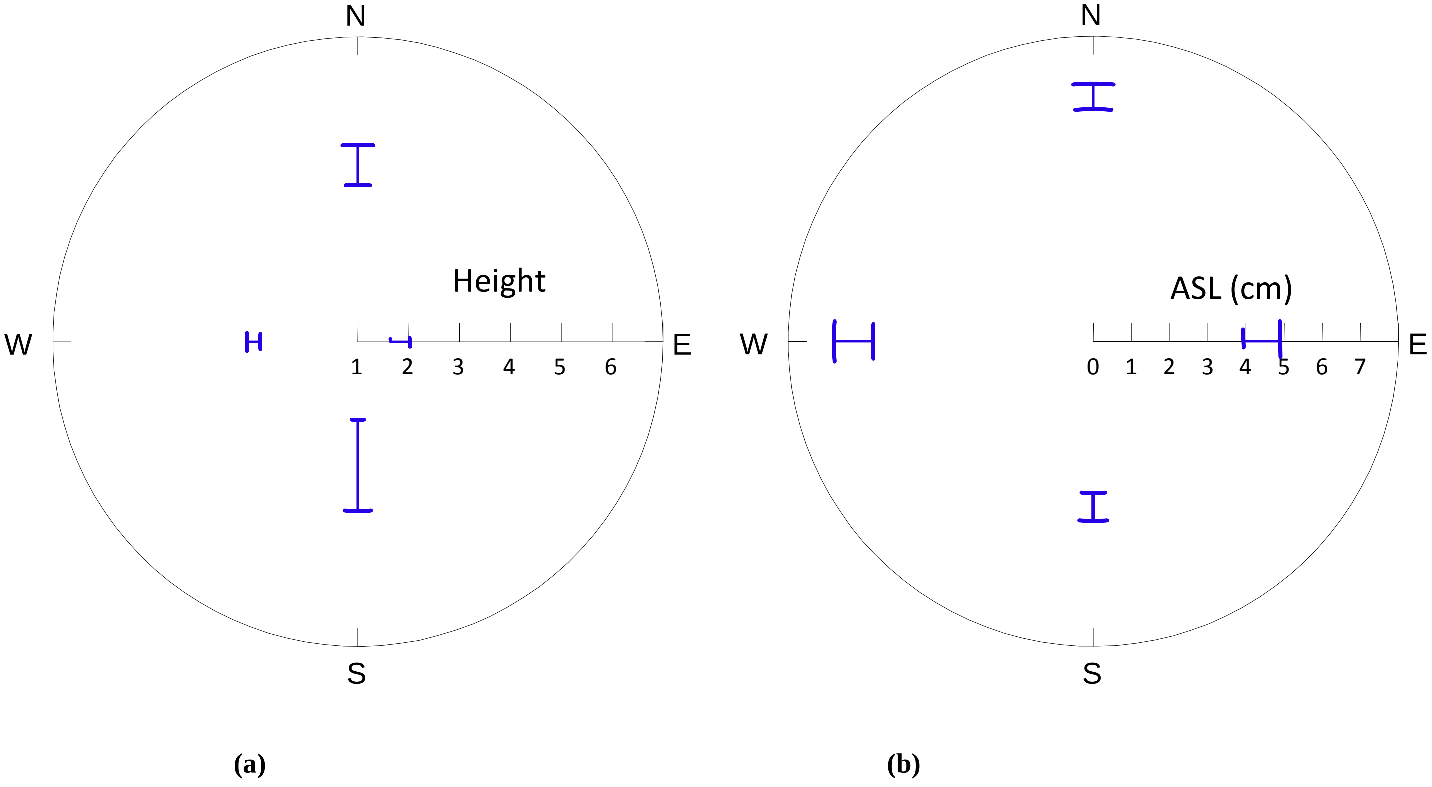


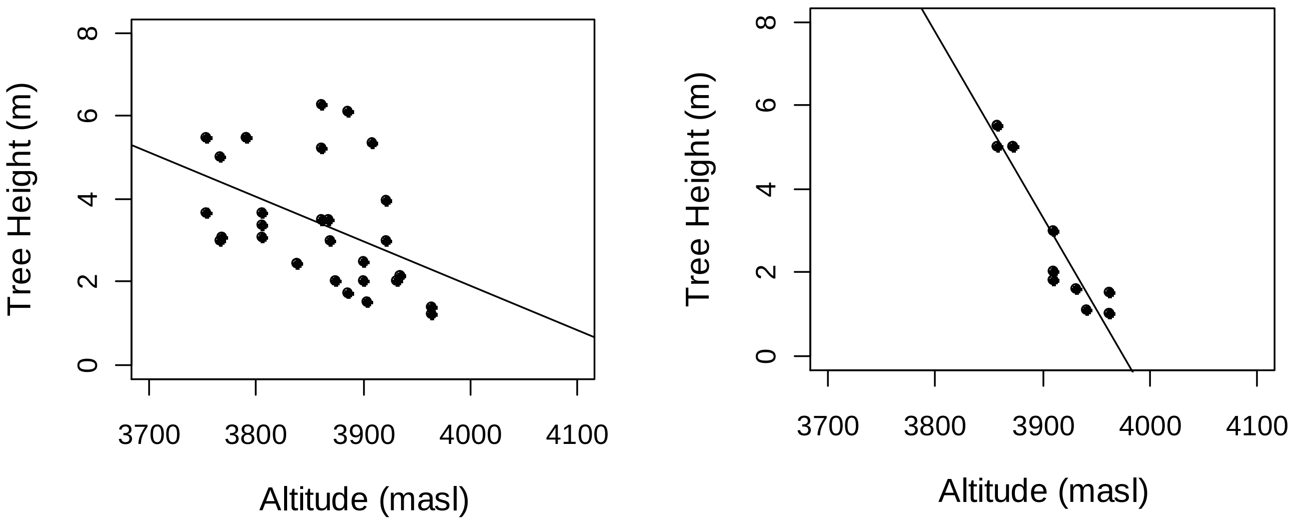
Fig. 6. Average height (a) and annual shoot length (b), according to the slope aspect.

3.1.3. Relation between altitude and height

In both species the tree height decreases as the altitude increases (for *R campanulatum* F $_{(1,33)}$ = 9.58, p=0.004; for *R.campylocarpum* F $_{(1,15)}$ = 131.40, p=0.00) (Table 1, Fig .7) . However the fit of the relation was much better for *R. campylocarpum* (R^2 =0. 89) than for *R. campanulatum* (R^2= 0.20). This reduction in height occurred over a short distance (around 300 meter altitude difference for *R. campanulatum* and 100 meter for *R.campylocarmpum*).

Table 1. Regression diagnostics describing the relation between tree height and altitude for *Rhododendron* spp.

Specie	R^2	Coeff	SE	Intercept	SE	F	Df	Dfres	P
R.campanulatum	0.20	-0.011	0.003	45.89	14.20	8.51	32	1	0.006
R.campylocarpum	0.89	-0.045	0.004	177.08	15.16	131.4	15	1	$p<0.001$

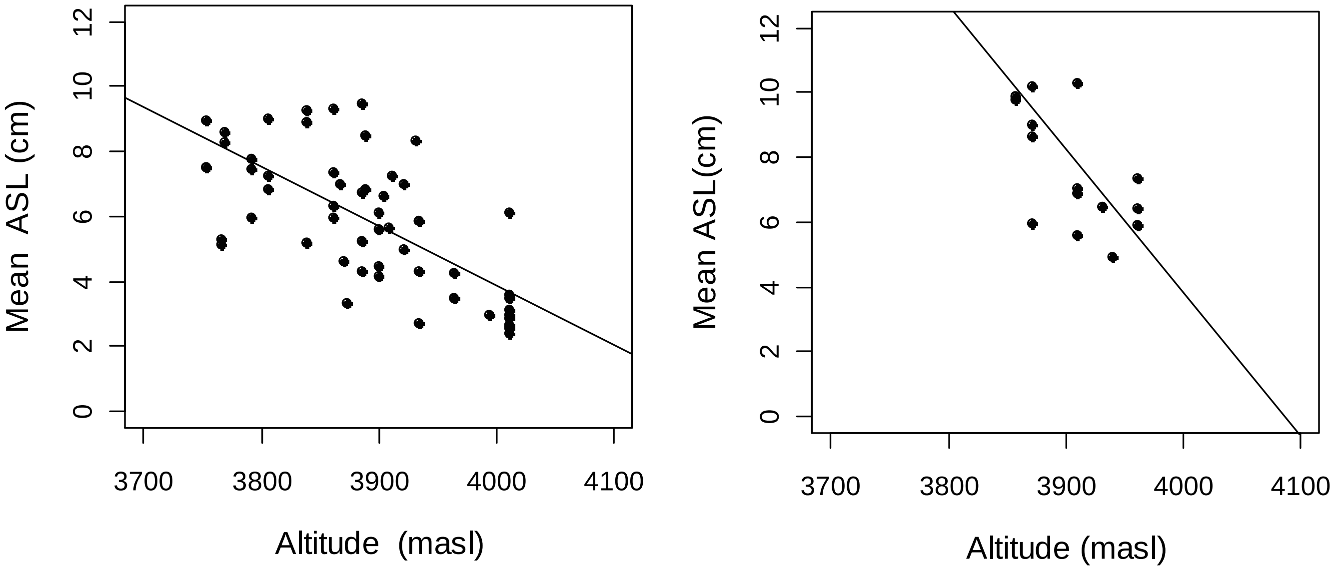


(a) **(b)**

Fig. 7 Relation between tree height and altitude for (a) *R. campanulatum* (n=33) (b) *R. campylocarpum* (n=17)

3.1.4. Relation between altitude and annual shoot length

A significant negative relation between annual shoot length and altitude was found for both species. Fig.8 shows the mean annual shoot length for years 2001 to 2007, for both species. Approximately, 45% of the variation observed in the annual shoot length is related to the altitude in both cases (*R. campanulatum* : R^2= 0.46 , $F_{(1, 54)}$= 47.166, p= 0.000; *R. campylocarpum* : R^2= 0.45 $F_{(1, 15)}$ = 14.16, p= 0.002).



(a) **(b)**

Fig. 8. Relation between annual shoot length and altitude for (a) *R. campanulatum* (n=56) (b) *R. campylocarpum* (n=17)

In all the years studied (2001 to 2007), as elevation increases there is a decrease in the annual shoot length. Table 2 and 3 present the regression coefficients for each species.

Table 2. Regression diagnostics describing the relation between altitude and annual shoot length by year for *R. campanulatum*, for the years 2001 to 2007, and mean annual shoot length for 2001-2007.

Year	R^2	Coeff.	SE	Intercept	SE	F	Dfres	Df	P
2007	0.46	-0.020	0.003	82.03	11.05	48.42	1	54	0.00
2006	0.43	-0.019	0.003	80.38	11.50	42.91	1	54	0.00
2005	0.22	-0.014	0.004	61.57	13.70	16.80	1	54	0.00
2004	0.37	-0.019	0.003	78.17	12.53	33.40	1	54	0.00
2003	0.32	-0.019	0.004	79.76	13.94	27.85	1	54	0.00
2002	0.25	-0.017	0.004	71.93	14.95	19.20	1	54	0.00
2001	0.42	-0.021	0.003	88.05	12.74	40.83	1	54	0.00
Mean ASL	0.46	-0.018	0.003	77.41	10.41	46.46	1	54	0.00

Table 3. Regression diagnostics describing the relation between altitude and annual shoot length by year for *R. campylocarpum*, for the years 2001 to 2007, and annual shoot length for 2001-2007.

Year	R^2	Coeff	SE	Intercept	SE	F	Df reg.	Df res.	P
2007	0.51	-0.048	0.011	192.08	44.58	17.38	1	15	0.001
2006	0.25	-0.035	0.014	144.70	54.65	6.36	1	15	0.023
2005	0.46	-0.045	0.012	181.72	45.45	14.60	1	15	0.002
2004	0.49	-0.044	0.011	181.22	42.67	16.40	1	15	0.001
2003	0.51	-0.041	0.010	167.29	38.03	17.45	1	15	0.001
2002	0.32	-0.057	0.019	231.58	75.36	8.65	1	15	0.010
2001	0.25	-0.041	0.017	170.19	64.41	6.21	1	15	0.025
Mean ASL	0.45	-0.044	0.0112	181.25	45.98	14.16	1	15	0.002

3.1.5. Difference in growth rate for *Rhododendron* species

The rate of decrease in height is significantly different between the species (Table 4). Comparison of the reduction in annual shoot length with altitude revealed that annual shoot length in *R. campylocarpum* reduced more rapidly with elevation than *R. campanulatum*. *R. campylocarpum* reduces 4.5 cm while *R. campanulatum* reduces only 1.1 cm in tree size for every meter gain in elevation. A similar response is observed for each year’s shoot length, except for 2006 and 2001 (Table5).

Table 4. T-test results for the difference in reduction rate in height due to altitude for the two *Rhododendron* species.

Variable	t	df	P	$t_{\alpha/2, 0.05, 48}$
Height	6.01	48	0.0	1.68

Table 5. T-test results for the difference in reduction rate in annual shoot length due to altitude for the two *Rhododendron* species.

Variable	T	df	P	$t_{\alpha/2, 0.05, 65}$
Mean ASL	2.10	65	0.03	1.67
ASL 2007	2.46	65	0.01	1.67
ASL 2006	1.12	65	0.26	1.67
ASL 2005	2.45	65	0.01	1.67
ASL 2004	2.19	65	0.03	1.67
ASL 2003	2.04	65	0.04	1.67
ASL 2002	2.06	65	0.04	1.67
ASL 2001	1.16	65	0.25	1.67

3.2. Analysis of snow cover permanence and annual shoot length

Snow cover varied between years (Fig 9), both for FSC>10% and FSC>50% ($F_{(6,28)}$=34.04, p = 0.00). Fig. 9, shows that there is fluctuation between the years, 2007 presented the maximum amount of snow, while 2001 had little snow. Visual comparison of the median annual shoot length per year (Fig.5) and the variability of snow cover between years does not revealed any pattern. While the size of the shoots tends to decrease from 2001 to 2007, snow cover oscillates between years.

In most of the years at higher altitudes there is more snow cover, however in some years there is slightly more snow cover at 3750 meters than at higher altitudes (Fig. 10). This might be due to the fact, that the estimated elevation is an approximation of the average altitude per pixel. Therefore, variability in altitude could be masked, if within the same pixel there are low areas and high peaks. The spatial resolution of the images, is probably limiting the variability that can be observed in the altitude.

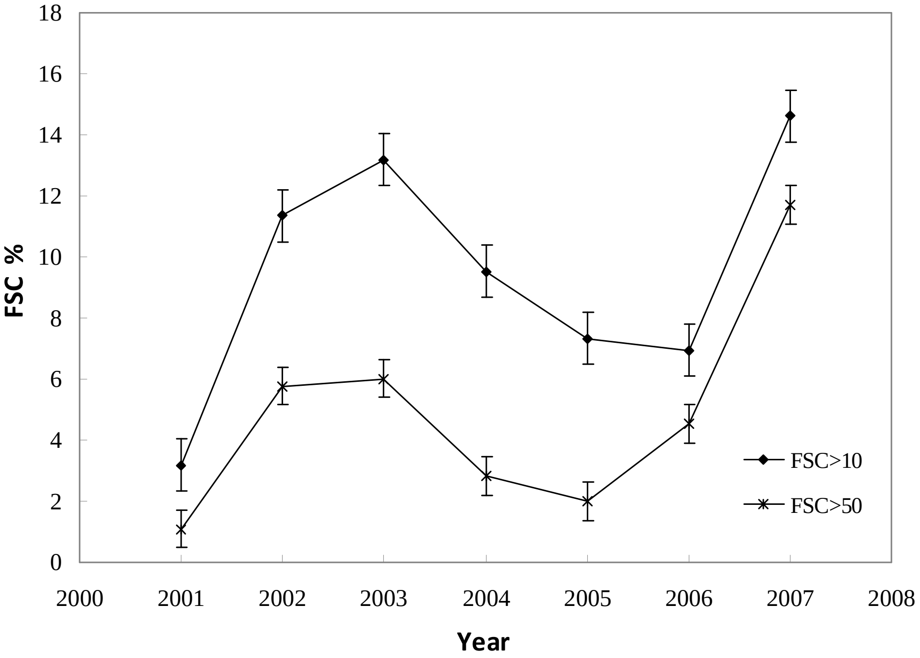


Fig. 9. Mean fractional (+SE) snow cover per year

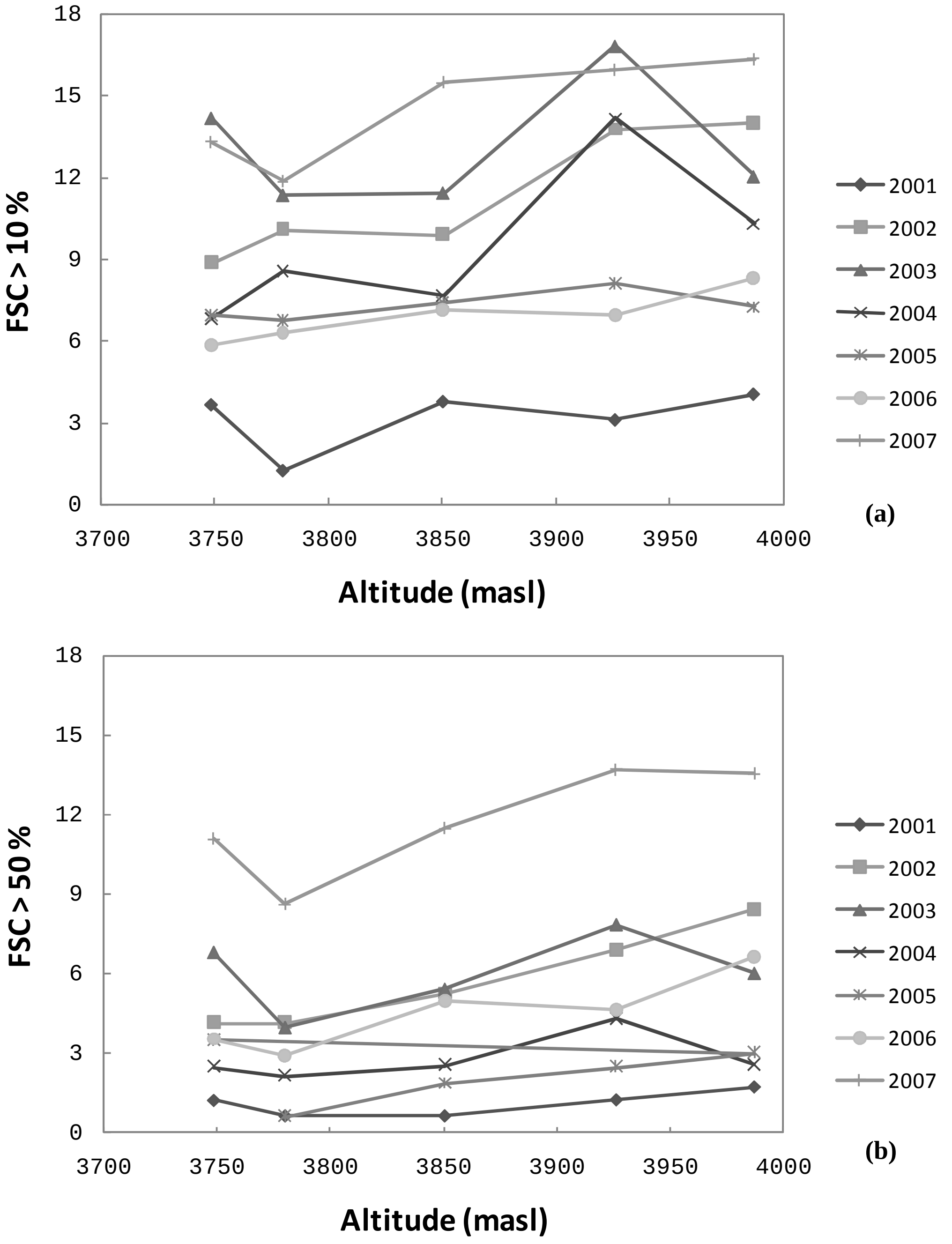
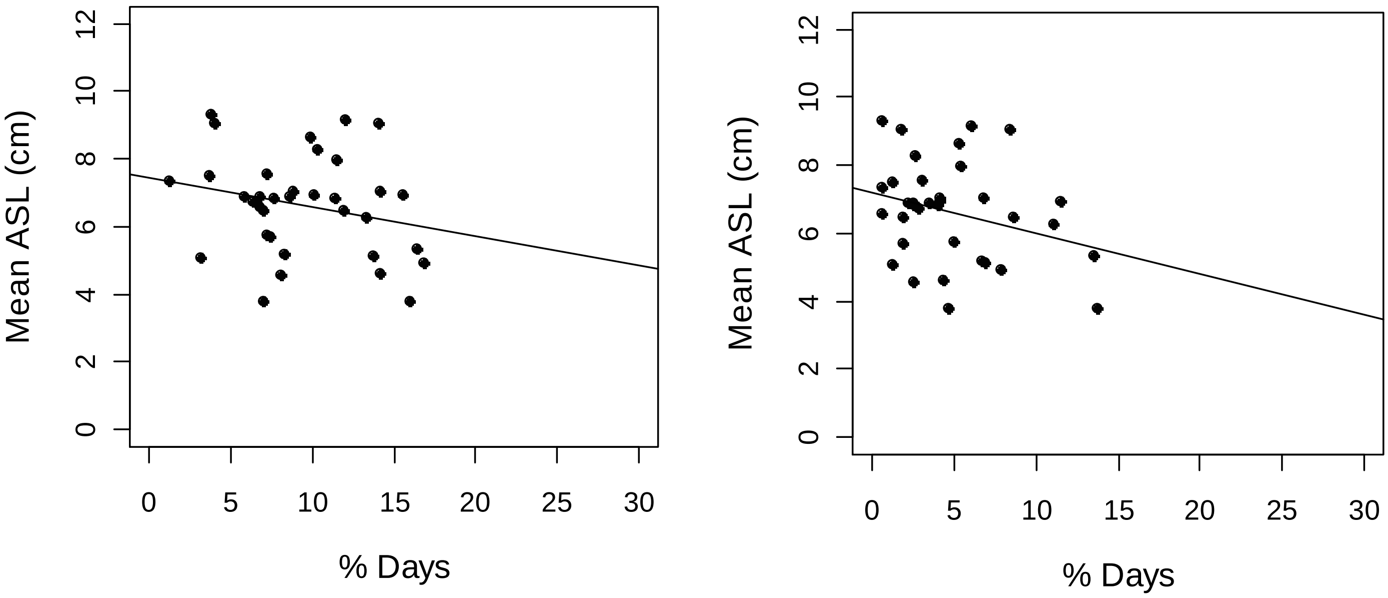


Fig. 10. Year to year variation in the number of days (percentage of reported days) in which FSC was more than 10% (a) and 50% (b), according to the average altitude per pixel.

No association was found between the number of days when FSC was above 10% and 50% and the length of the shoots (Fig.11). The analysis between the number of days in which snow was reported to be more than 10% and the shoots revealed no significant relation (R^2=0.032, $F_{(1,33)}$=0.465, p= 0.155). A similar result was obtained when analyzing the number of days in which snow cover was high, FSC >50% (R^2=0.057, $F_{(1, 33)}$ = 3.059, p=0.090). The p-values are in both cases close to the critical value of α= 0.05. Formally this would lead to failure of rejecting the null hypothesis and to conclude that there is no evidence that snow cover relates to annual shoot growth. Given the small sample size, the chance of type I error is high. Therefore we draw the above conclusion with reservations and suggest that further research with a larger sample size covering a broader altitudinal range should be considered.



(a) **(b)**

Fig. 11. Relation between the annual shoot length and the FSC for *R. campanulatum* a) Percentage of reported days with FSC >10% b) Percentage of reported with FSC >50%, (n=35)

3.3. Analysis of growing season length and annual shoot length

The growing season length analysis was done by modelling 11 pixels where *R.campanulatum* plants where sampled. Fig.12 present an example of the fit curve obtained with the three fitting methods for a pixel (row 5 column 11).

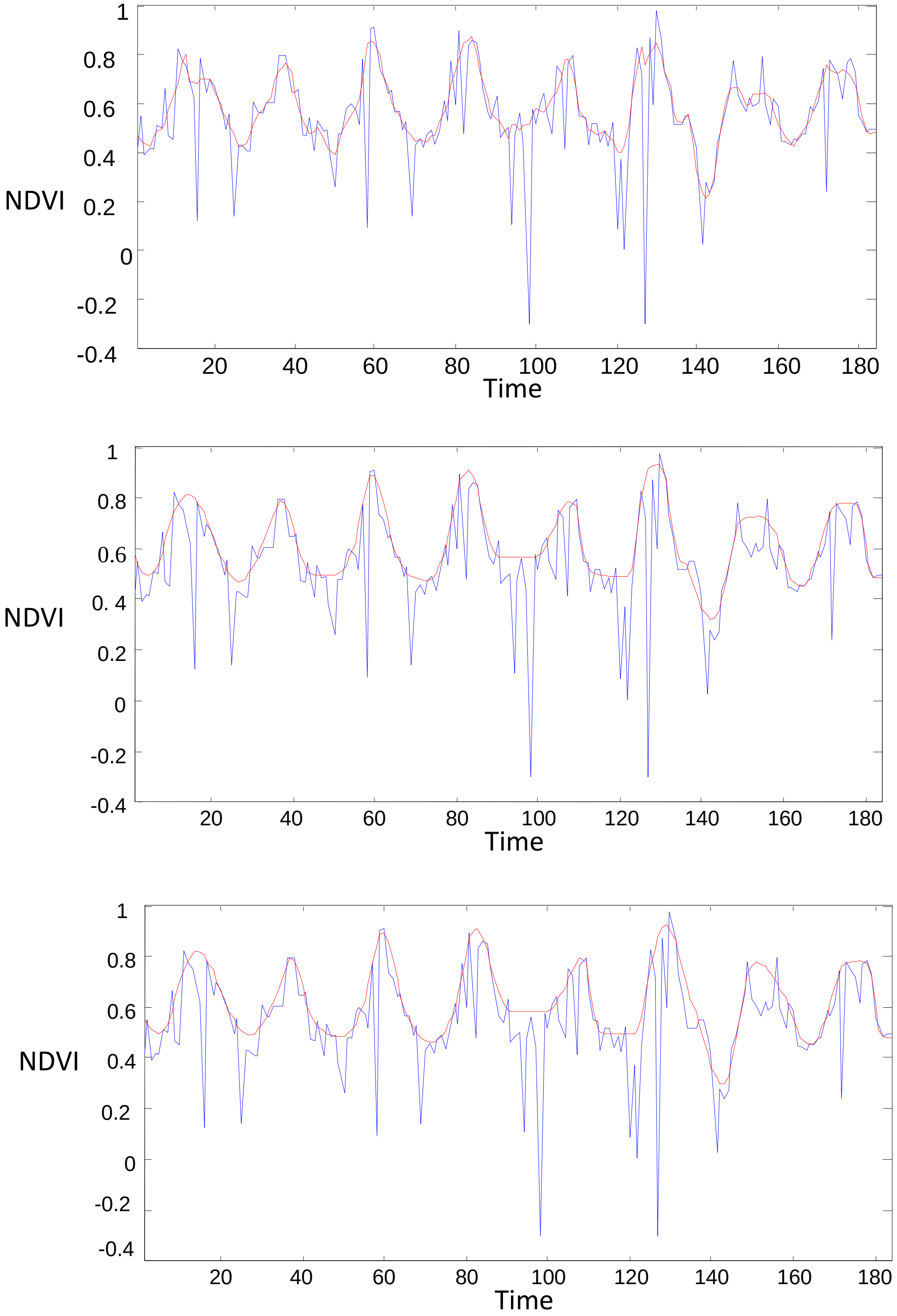


Fig. 12. Example of the three smooth methods for the pixel a) Savitzky Golay b)Assymetric Gausian c) Double Logistic

The estimation of the growing season length differ significantly between years (SG: $F_{(6,70)}=5.19$, $p<0.001$, AG: $F_{(6,70)}=2.55$, $p=0.02$, DL: $F_{(6,70)}=2.77$, $p=0.018$). The three smoothing methods predicted the a shortest growing season in 2004 and 2001 as the longest (Fig.13).

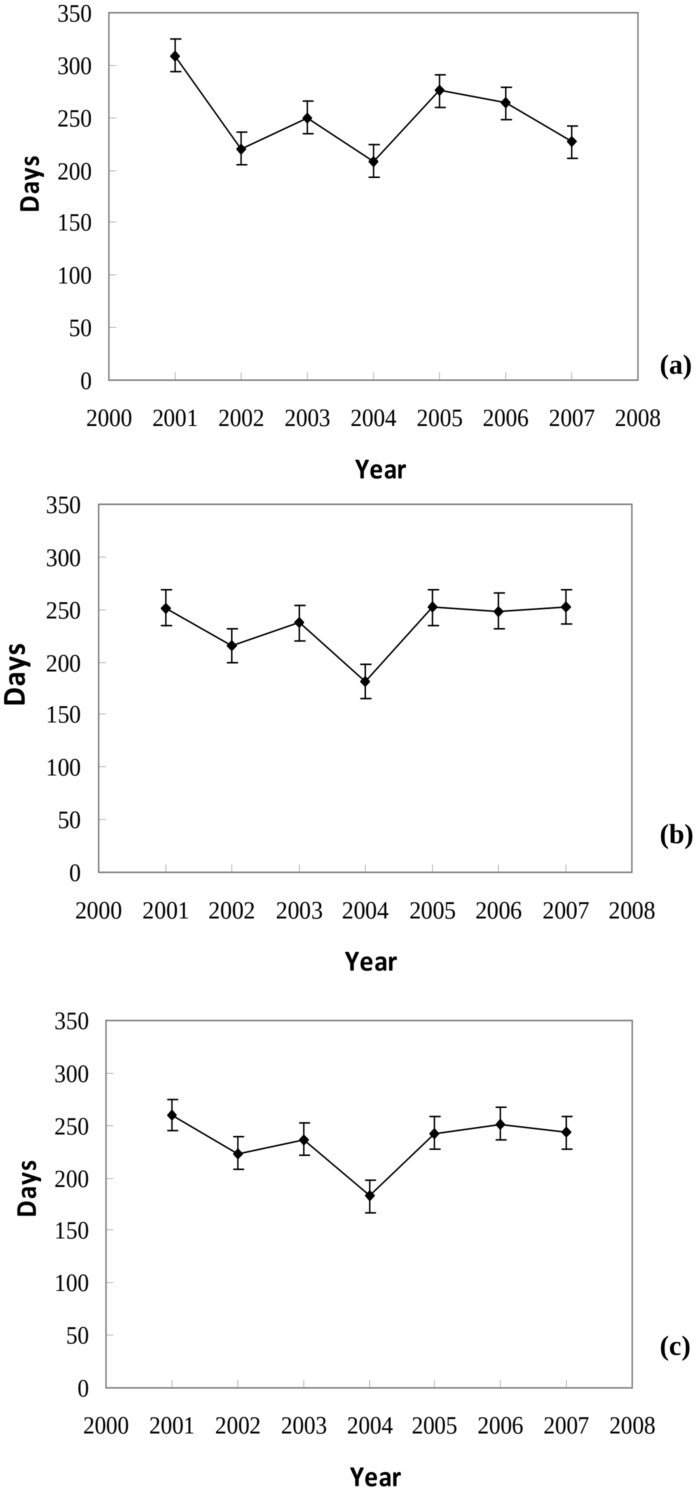
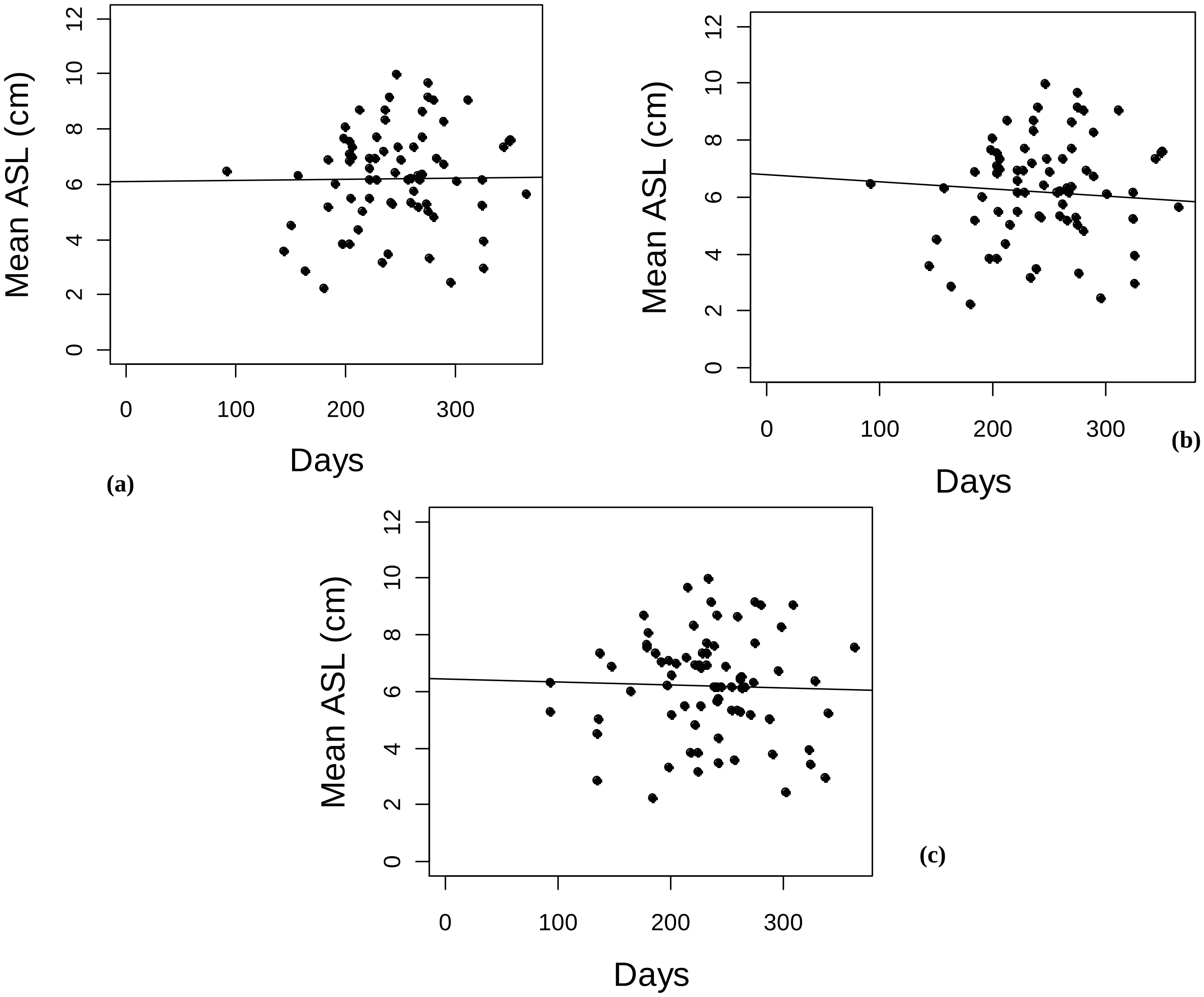


Fig. 13. Mean growing season length per year (+SE) estimated by a) Savitsky Golay b) Assymetric Gausian c) Double Logistic, fitting methods

From the obtained data, it appears that there is an overestimation of length, because in some cases the length of the growing period was predicted to be 300 days (Fig 13). However, since there are no ground truth measurements, such as budburst, the obtained values could not be validated. The flowering of the rhododendrons at these altitudes begin around April or May, sometime after the growing season has started; and it is estimated to last between 6-9 months (de Milleville, 2002). Unfortunately, there is no detailed information on its spatial variability, since this is just an approximate for the whole altitudinal gradient and for several species.

No significant relation was found between the duration of the growing season and the annual shoot length irrespective of the function used to smooth the NDVI time series (Fig.14) (SG: R^2= 0.0 F $_{(1,75)}$= 0.017 p= 0.897: AG: R^2=0, F $_{(1,75)}$ =0.49, p= 0.48; DL: R^2= 0.0, F $_{(1,75)}$= 0.104, p= 0.747).



(a)

(b)

(c)

Fig. 14. Relation between the annual shoot length and growing season length as determined by the three fitting functions a) Savitsky Golay b) Assymetric Gausian c) Double Logistic (n=77)

3.4. Annual Shoot Length Growth Model

A GLM was build to evaluate the effect of the environmental variables on IND of *R. campanulatum.* The effect of snow cover, length of growing period, altitude, shoot's age, and the interaction between altitude and age was estimated through stepwise regression. Only altitude and age were significant variables for predicting the size of the shoots:

$$ASL= 71.10 -0.017ALT+ 0.30\ AGE \qquad (R^2 = 0.37, n=392, F_{(2,389)}=113.33, p <0.001)$$

Although the R^2 is low, the t values for the altitude and age were high and highly significant (t_{age}= 6.08, $p<0.001$, t_{alt}= -13.77, $p<0.001$).

Duration of snow cover and growing season varies with altitude (Tranquillini, 1964).When these variables depend on altitude, its effect might have been taken along in the model indirectly. Table 6 revealed that correlation coefficients were low although all the variables were significantly correlated. As the variables are partly dependent on altitude, its effect, although small, is considered in the model indirectly.

Table 6. Correlation coefficients between altitude and snow cover and growing season length

Variable	ρ	t	P
Snow10	0.23	4.61	p < 0.001
Snow50	0.16	3.26	0.001
Days SG	0.095	1.88	0.06
Days AG	0.24	5.01	p < 0.001
Days DL	0.21	4.38	p< 0.001

The application of the model to the different shoot's ages is shown in Fig.15. The model predicts a proportional decrease, the younger nodes, the ones produced in 2007, present the smallest annual shoot length at all altitudes. As shown in Fig. 15, at different altitudes the decrease in annual shoots of the same age is approximately 1.7 cm for every 100 meter gain in elevation for *R. campanulatum.*

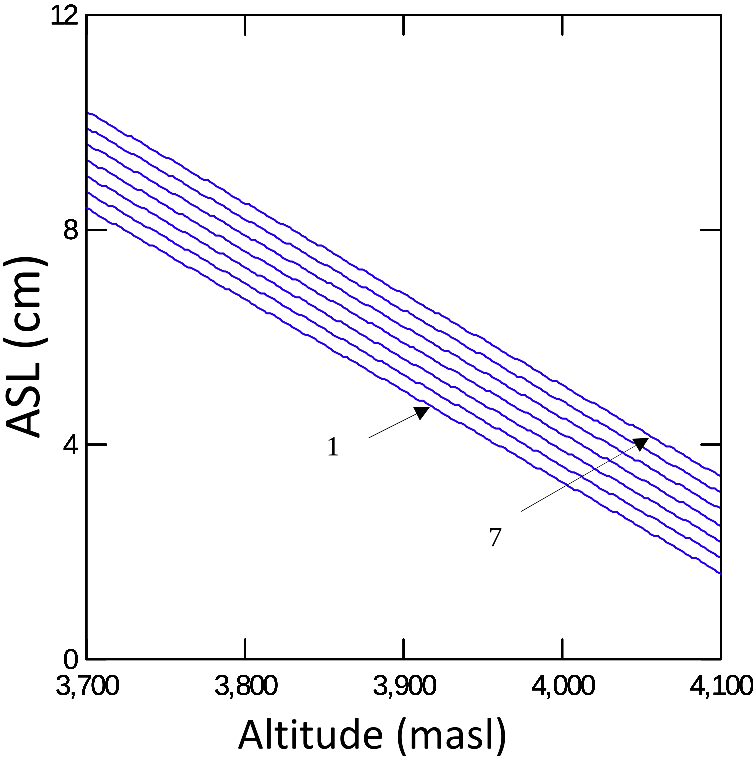


Fig. 15. Annual shoot length for *R. campanulatum* at different ages plot by altitude as predicted by the model (Plot function Y=71+0.03 *AGE (1-7)-0.017*X), each line represents the change in annual shoot length at different altitudes and at different ages. The lowest values correspond to 1 year old annual shoots and the highest to 7 year old shoots.

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4. Discussion

This research was initiated with the idea to investigate the relation between two complementary environmental factors, snow and growing season length, and the growth of two *Rhododendron* species along the treeline. It was expected that the length of the annual shoots would be related to the year to year variability of snow cover permanence which we assumed would also affect the length of the growing season. We failed to reject these two null hypotheses, probably because the sample size was very small and covered a very small altitudinal gradient which makes it difficult to detect the variability associated with the studied environmental factors.

However, insights on the growth of *Rhododendron* species, in relation to the aspect and altitude were gained. An interesting result was the high degree of dependence between the length of the annual shoots and the altitude, as well as between the tree height and the altitude. Our data, made it possible to estimate the rate to which rhododendron branches and trees were reducing in the East Himalayan treeline. To our knowledge this has not been reported before.

The following paragraphs describe the obtained results and the possible explanations in more detail. Beginning with the observed spatial variability and finalizing with the analysis of the derived model.

4.1. Spatial variability of growth

This research demonstrated that there is spatial variability in the growth of two *Rhododendron* species that is associated to aspect and altitude. In the case of the aspect, both height and mean annual shoot length of *R. campanulatum* showed differences between the aspects of the sites where plants were growing (Table 1, Fig. 6.). Taller trees where located facing north, while north and west facing slopes had longer annual shoots than south and east facing slopes.

The aspect plays an important role in determining where the rhododendrons grow. In Nepal, most of the species that developed in forested areas prefer, north-east facing slopes (Shakya, 1999). According to Schickhoff (2005), in the Himalayas north facing slopes present more favourable topoclimatic conditions for the development of vegetation than south facing slopes. Due to high irradiation received on south facing slopes, evaporation and drought stress is high, which limits vegetation growth.

Several authors have studied how high amounts of radiation affect high altitude vegetation. In an studied done by Cramer (1997) in (Schickhoff, 2005), considerable differences in radiation intensity were found. He reported that on a clear winter day south facing slopes more radiation (1000 Wm^2) than north-facing slopes (77 wm^2). Similarly Bader & Ruijten (2008), studied radiation and aspect in the Ecuadorian Andes. They concluded that the high amount of radiation received in east-facing slopes could cause photoinhibition, which in turn affects growth.

Therefore, the observed pattern, shorter annual shoots in south and east facing slopes, could be a consequence of high amounts of radiation inhibiting growth. Probably the north and west aspects, receive a balance amount of radiation, allowing the development of rhododendron forest with longer annual shoots. However the result could be affected by the sample amount which was less in south and east facing slopes, since *Rhododendron* forest were found mainly in north and west slopes.

Aspect is not the only factor influencing the growth. In this research it was demonstrated that there is a relation between the altitude and the growth of the annul shoots for *R. campanulatum* and *R. campylocarpum.* (Fig 7 & 8, Table 2 & 3). At lower elevations the annual shoot length tends to be longer in both species and trees are significantly taller, as well.

This reduction in the length of the annual shoots and in the tree height occurred over a short altitudinal range. Tree height reduced 3 meter over a difference in elevation of 300 meter. The reduction is accompanied by morphological changes observed in the field, trees become more branched and their central stems become more conspicuous with increasing elevation (Tranquillini, 1964).

Therefore if trees are decreasing in height (Fig. 7) and shoots are shortening with elevation (Fig 8), and this pattern is observed in all the years studied (Table 2 & 3), it is an indication that altitude is influencing the shoot growth rate of *R. campanulatum* and *R. campylocarpum*, causing the observed tree dwarfing.

However altitude *per se*, does not influence the shoot growth rate. Environmental factors related to altitude might account, at least partly, for the variability observed in annual shoot growth and height. These environmental factors associated to the altitudinal gradient should be influencing the plants growth internal control mechanisms. A combination of factors such as air temperature, soil moisture and amount of solar radiation could trigger the trees control mechanisms of growth. Further research on these aspects is required on the study area to assess the sources of variability observed in the relation between annual shoot length and altitude.

The response in height and annual shoot length to elevation differed between the two species (Table 4 & 5). *R. campylocarpum* presented a stronger reduction in height and annual shoot length than *R. campanulatum.* This fact might explain the lower upper distribution of *R. campylocarpum* (3900 masl) compared to 4400 m for *R. campanulatum* and is reflected on the distribution range of the species.

It seems that *R. campanulatum* which present a wider distribution range and a lower reduction on annual shoot's growth rate, is able to develop over a larger set of growth conditions associated with altitude. *R. campylocarpum*, which is constrainted to a 200 meter distribution range, response more dramatically to the changing environmental circumstances. So both species reduce their growth rate in order to be able to cope with the harsh environment, but *R. campylocarpum* apparently has adaptation mechanisms that limit the species to occur over a smaller altitudinal range.

The observed relation between growth of the two *Rhododendron* spp. altitude and slope could be explained by the interaction between tree morphology and microclimate. According to Körner (1998), the morphological changes associated to the treeline could be due to a threshold temperature under which tissue growth and differentiation could not take place.

The life form-tree is coupled tightly to the environment (Wieser, 2007). It cannot store warmth in the topsoil during the night, because trees experienced convective cooling. This maintains the root zone, under the tree canopy cold. This cooling inhibits the production of tissue during a substantial part of the year and during most of the nights. Trees could experienced longer periods of inhibition of tissue production as altitude increases because low soil temperatures become more common and therefore trees turn out to be smaller (Körner, 1998; Körner & Hoch, 2006).

Trees also might regulate allocation of resources in a way that will be the most beneficial for conserving heat. Physiological mechanisms, such as apical control (Wilson, 2000; Suzuki & Suzuki, 2009), could play a role on producing a tree-architecture that maximizes the conservation of heat in the top soil and therefore enhance tissue production. In apical control, elongation of the nodes is determined by the position of the apical meristem in relation to the central stem of the tree and the position of the branch, so in this way the tree control the growth rates of annual shoots.

In conclusion, there is a high degree of complexity in the interactions between topography, microclimate, tree morphology and physiology. The observed reduction in tree height and annual shoot length in *Rhododendron* species could be consequence of such interactions. However further investigation, e.g. root zone and air temperature measurements, will be needed to assess the response of this parameters on the growth of these species.

4.2. Snow cover permanence and annual shoot length

No relation was observed between the annual shoot length and the fractional snow cover (Fig. 11) even though there is variation between the years in the amount of snow (Fig. 9) Can it be concluded that snow cover permanence is not a determinant factor on the growth of *Rhododendron* species at the treeline?

Several authors have reported that snow is not a determinant factor controlling growth in relation with mechanical damage (Körner, 1998). Normally, high altitude plants have cold hardiness higher than the actual environmental demand (Sakai & Malla, 1981; Wieser & Tausz, 2007). Sakai &Malla (1981) reported for *R. campylocarpum* and *R.campanulatum* a freezing resistence of -30°C and -35°C, respectively for leaf bud. This temperature is much lower than the average winter temperatures of the study area.

Obviously, this adaptation allows the plants to overcome winter without tissue damage. However, tissue damage can occur when sporadic episodes of light frost during the growing period take place, which are more common in the tropics, because freezing damage could occur at any time of the year (Körner, 2003). Since the study area is subtropical, it is possible that tissue damage is not such an important factor for the growth of rhododendrons, since the species present high winter hardiness. However the effect of sporadic frost is unknown.

In addition is possible that the size of the annual shoots will not be affected by snow presence at all. Even though there is less snow in a year (Fig.9) and therefore longer growing season, the annual shoots will not elongate more than a definite amount, in order to maintain certain tree architecture, as explained before. As a result the size of the annual shoot will be in a higher degree a consequence of physiological or genetically determined mechanisms than a result of snow presence.

Besides the ecological responses or physiological factors that could explained why there is no association between snow and annual growth length, the limited variability owing to spatial resolution of MODIS data should be analyzed. The study area is a mountainous terrain with sharp slopes. As a consequence, the same pixel could cover a wide altitudinal range and different slope aspect. Snow variability associated to higher elevations is masked because at the end the information extract from each pixel is a generalization of a large array of altitudes and slopes. This is support by the pattern present in the snow curves variation according to average altitude of each pixel (Fig.10), in which some lower altitudes present more snow cover than some higher altitudes.

Another factor that is influencing the result are the difficulties associated to the mapping of snow in evergreen forests (Kimball *et al.*, 2004; Beck *et al.*, 2005; Ault *et al.*, 2006; Delbart *et al.*, 2006). Even though the FSC is validated to stage 2 and the used images were classified as good quality (Appendix B), evergreen forests limit the quantification of snow. Since vegetation gets in between what it can be observed on the ground, snow is hard to detect.

To conclude, there are limiting factors that make it difficult to really evaluate the effect of snow on the growth of *Rhododendron*. The results presented here do provide insights on the behaviour of snow in the area and the interaction with growth. However, further research is needed on specific responses, such as the response of vegetation to sporadic frost episodes. Moreover detailed mapping of snow patterns and snow depth of the study area during long periods will be required to assess the effect of the snow on the growth of the annual shoots of rhododendrons.

4.3. Growing season length and annual shoot length

The size of the annual shoots did not present a linear respond to the growing season as determined by the NDVI 16 day composites and the three smoothing functions (Fig.14). Even though there was significant variation between the lengths of the growing season in each year (Fig. 13), longer annual shoots did not relate to with predicted longer growing seasons. Several aspects might be influencing the obtained relation between growing season length and the annual shoot length.

The first aspect that might be affecting the result is that the three functions determined growing season lengths that are overestimated. According to de Milleville (2002) the growing season in these areas should be between 6 to 8 months (around 180-250 days). In some cases, the calculated growing season length more than 300 days, but as shown in Fig 13, most of the years the growing season length lasted more or less 250 days.

It is difficult to calculate the magnitude of this overestimation, since there is no reference in the literature (to our knowledge) specific for the area to compare these results with. However, in general one of the problems with satellite-based phenological studies is that for evergreen vegetation is difficult to determine the onset and the end of the growing period because the leaves are always present and snow does not stay on the canopy (Fisher & Mustard, 2007). Consequently there is a tendency to overestimate the growing season length.

Nevertheless, TIMESAT have been used successfully to model time series and nowadays it is been used to produce new phenological products based on MODIS (Tan *et al.*, 2007). In this sense, the application of this software should produce reliable results. To improve the results obtained with TIMESAT for high latitude forests many authors have applied algorithms to account for the snow effects on the NDVI determination (Jonsson & Eklundh, 2002; Zhang *et al.*, 2003; Delbart *et al.*, 2005; Yu *et al.*, 2005; Beck *et al.*, 2006; Delbart *et al.*, 2006; Fisher & Mustard, 2007; Karlsen *et al.*, 2008). In this case, such algorithms were not applied due to the small sample size; certainly the estimate of the growing season length could be improved if such algorithms were used in a larger area.

A third aspect that should be addressed is the difficulty of associating low spatial resolution images with field data. Many studies recognized the limitation for relating ground-based to satellite-based observations due to scale incompatibilities (Schwartz, 1999; Fisher & Mustard, 2007; Sirguey *et al.*, 2009). Single tree based observations are supposed to represent the behaviour of the whole forest as it captured by the satellite. This is extremely difficult in landscapes with high variability cause by topography, such as the Himalayas. At the end, the high spatial resolution of MODIS pixels smoothed the local variability, that can be cause the microclimates or sharp topography as the one present in the *Rhododendron* species.

Finally, it is out of the scope of this study to analyze the variability in growing season length due to the different fitting functions (Fig.12). Several authors have applied different algorithms to the diverse functions obtaining different degrees of accuracy. However, it is probable that the double logistic function gave the best approximate to the growing season length, because it has been used for coniferous forests and mixed forests in northern latitudes.

4.4. Annual Shoot Growth Model

After analyzing the spatial variability showed by *R. campanulatum*, along the treeline altitudinal gradient and studying the possible relation to the environmental factors, snow cover and length of growing season, several GLM models were built. From all the models, only the age of the shoots and the altitude presented significant effects (Fig.15). Even though the chosen GLM does not gave a very high percentage of the explained variation in ASL (R^2 =0.36), the t-values are extremely low, especially for the altitude. There are two possible sources of error that explain the relatively low $R^{2.}$

The first source of error is the measurement of the annual shoots. The scar of the leaves is distributed over a small area, so variability is introduced on the measurements depending on where the reading, somewhat subjective, was taken. Besides, there is also instrument error deriving from the use of a metric tape which has an uncertainty of 0. 5 mm.

A second source of error, that is probably quite important, is the one deriving from the age of the branches and the plants. It has been reported that plants control the size of their branches depending on the distance to the main stem (Wilson, 2000). This sort of control known as apical control, will produce longer nodes are closer to the main stem (and therefore older) and will start decreasing in size as they grow away from the main stem. Plants have these mechanisms as a way to control tree architecture. The observed small distance in younger annual shoots than in older ones is possible related to this system (Fig 5). The tree architecture will vary depending on the age of the tree, therefore the respond in the growth will be different depending on the age.

5. Limitations of the study

1. In order to assess in a more conclusive way the effect of the aspect in the height and annual shoot length it is necessary to sample in more areas located in the south and east slopes. The data obtain here could only provide an indication of the pattern. Systematic data collection on slopes facing the four directions, at different altitudes is necessary to deeply evaluate the spatial variation of growth associated to the aspect.

2. Images spatial resolution was an important limiting factor. The field data was clustered in very few pixels, which affected the strength of the statistical tests and lead to errors related to non representative samples. It was not possible to sample in a larger area, mainly because of the difficulties associated with the topography. The sampling scheme used in this study should be improve in future works. A larger altitudinal gradient should be sample to better access the differences in snow and growing season length. Other areas along the East Himalaya Mountain Range will need to be included. Previous identification of the MODIS pixels using vegetation maps for selecting the sampling sites is also recommended. However, it is difficult to improve the design applied here, because at end all these mountain areas need to be reach by foot, which limits the possibility of data collection.

Even though the coarse resolution of MODIS time-series, it represented the best way to study the growth record based on annual shoot length, in terms of temporal and spatial resolution, and cost. The use of time-series allowed to explore the fact that each year could be associated to an annual shoot length and therefore to a specific image.

3. The impossibility of determining the branch and tree age affected the results. There is variability in the annual shoot length owing to the age of the tree. Ideally, the sampling design should determine the age of the trees and included trees of different ages at every altitude belt. It is very difficult to access the age of trees, tree ring analysis will be the way to do it. The problem with tree ring analysis that the rings in *Rhododendron* are quite conspicuous and could only be counted in a reliable manner using a microscope (Prof. M. Suzuki, pers.comm.). Since the study area was a National Park, it was not allow to take vegetative material out of it.

4. The study was based on the reliability of the quality assessment information layer provided with the MODIS products (Appendix B, E &F). It was out of the scope of this work, to investigate how to improve the results by analyzing the pixel quality. Basically because the limited data was associated to specific pixels and it make no sense to select for modelling other pixels with better quality.

The research was more focus on the application of these data to solve ecological questions. MODIS time series represented the best available choice to try to answer such questions. Eventhough its limitations, the use of MODIS time series FSC and NDVI 16 day composite were the only approach that allowed to relate the year to year information obtained from the annual shoots length with satellite-data.

Even though, it must be emphasize that the FSC product is a new product, which has only been validated to stage 2. This means that it has only been proof sufficient under a limited amount of areas, mainly in North America. It is expected that it will also be accurate in other parts of the world.

5. The lack of *in situ* climatological data on snow presence and snow depth did not allowed to cross validate the information obtained from the FSC MODIS products. In addition FSC is limited to snow presence, it does not include information on snow depth. Differences in snow depth could be an important factor affecting growth in high mountain ecosystems.

6. There are inherent limitations on the determination of the growing season in evergreen forest as discussed above. The aggregation of different vegetation types in the same pixel is another source of error. Although samples were taken in more or less homogeneous Rhododendron stands, there is variability due to the presence of other species.

6. Conclusions and Recommendations

This study was a first attempt to investigate local variability patterns on the growth of two *Rhododendron* species, which are the dominant vegetation growing at the treeline in the East Himalayas. It aimed to provide insights on the vegetation dynamics in this ecotone.

The spatial variability of growth for *R. campanulatum* and *R. campylocarpum* , as analyzed by height and annual shoot length, was demonstrated. The trees and annual shoots measured decreased in size and length as altitude increases. No relation was found between the snow cover and growing season length and the annual shoot length of *R. campanulatum.* As a result annual shoot length, altitude and shoot’s age were the most significant explanatory variables.

Spatial resolution is probably limiting the obtained result. As time–series with higher spatial resolution become freely available, similar studies could be done, and more conclusive evidence could be generated that support or decline the possible relation between the observed variability in growth and its relation with snow cover or growing season length.

6.1. Conclusions

1. A significant decreased in height and annual shoot length as altitude increases was identified for both rhododendron species. The rate of this decrease was higher for *R. campylocarpum* than for *R.campanulatum*. This might be view as a niche-based response, but is also an indication that in order to developed in harsh conditions present in the treeline in the East Himalayas the tree-form should have a certain morphology.

2. Spatial variability in growth was also associated to the aspect. Trees growing in east facing slopes presented significantly shorter annual shoot length than the ones growing in north and west facing slopes.

3. For the area analyzed, snow cover differs significantly between years. However, the annual shoot length of *R. campanulatum* was not associated to the amount of days in which snow cover was more than 10% or more than 50%.

4. The length of the annual shoots did not respond to the length of the growing season. Growing season length varied significantly between years, for all the functions used to smooth the NDVI time series. Analysis of the growing season length together with altitude did not improve the model.

5. The lack of relation between environmental parameters and annual shoot length suggest that physiological mechanisms control the size of branches and tree height. Furthermore, phenotypic response of tree architecture should have a limited range. Even though the conditions for growth at the treeline might be more favourable in some years than in others, trespassing that limit might result disadvantage for high altitude vegetation.

6. The observed growth pattern of the two *Rhododendron* species and the lack of relation between it and the snow cover and the duration of the growing season suggest that even though changes in climatic conditions occurred, treeline vegetation has a broad tolerance range to manage those changes. It seems that the growth of the annual shoot will not be altered due to low incidence of snow or longer growing periods, because of control mechanisms. As a result it is complex to assess the impact that climate change might have on the growth evergreen rhododendron forests at the treeline.

6.2. Recommendations

1. The relationship between annual shoot length and year to year temperature variability still remains to be investigated. This will require *in situ* measurements combined with satellite data. Though, satellite data for temperature time series, will present the same or even greater limitation of spatial resolution as the one encountered in this study for the FSC and NDVI.

2. It is also necessary to study the magnitude of the exposure to radiation to further understand the effect of aspect over the morphological change of the vegetation at the treeline. Research on the radiation received by the plants at different altitudes combine with temperature data could broaden the understanding of the East Himalayan treeline.

3. Information on winter hardiness combined with detailed mapping of snow patterns and snow depth in the area, will be the most comprehensive way of analyzing the effect of snow presence on the annual shoot length. Satellite data is limited to an overall evaluation of the amount of snow present in the area at a certain moment, but since the area is a broken terrain, snow can last longer on certain patches. The effect of this long lasting snow patches on vegetation could only be studied using *in situ* snow data.

4. The relation between Ecosystem's Net Primary Productivity and annual shoot length is another interested possibility to explore. The estimation of the integrated NDVI for growing season to estimate the NPP, has been shown to relate better to the annual growth in ecosystems. Therefore it could be expected that the length of the annual shoot's respond to it.

5. The growing season length could be predicted more precisely by applying an algorithm such as the winter NDVI. This algorithm has given successful results in coniferous forest in the temperate areas. this could provide a better estimate of the days of the growing period, and therefore a more realistic result.

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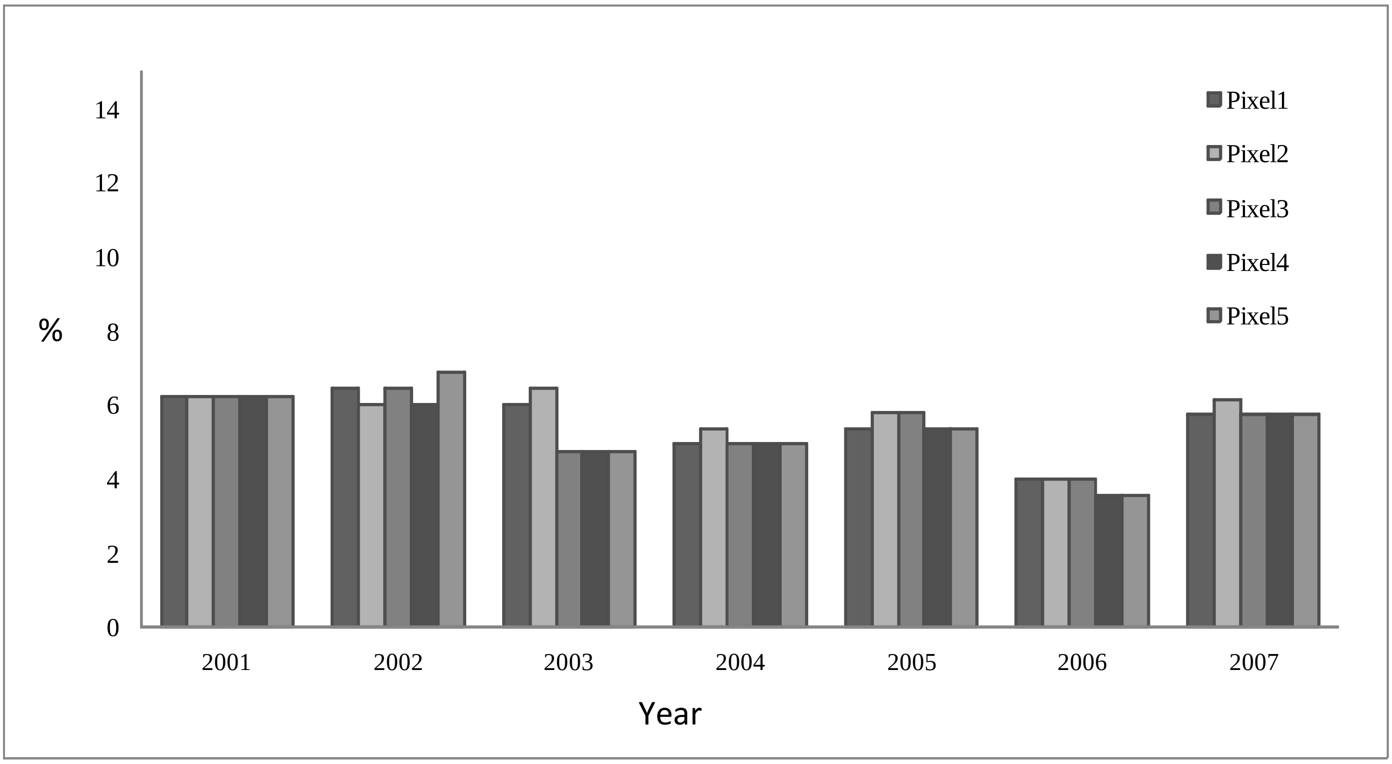
Appendix

Appendix A. Coordinates of the central point in each of the modelled pixels of MOD10A1

Pixel	Latitude	Longitude
1	27.8331741	86.767511
2	27.8340422	86.7717393
3	27.8375704	86.7729714
4	27.8433387	86.7812039
5	27.8437308	86.7849001

Appendix B. Summary of non quality data by pixel and by year for MOD10A1

Percentage of images with Quality assessstment values classified as non quality (values = 1, 253 or 255) for each year in FSC series 2001-2007 .



Appendix C. Available NDVI 16 composite per year, and replacement of missing composites

Year	Composite % available by year	Missing Composite*	Replacement Composite *
2001	100	-	-
2002	70	49	33
		65	81
		161	145
		177	145
		193	225
		209	225
		241	257
2003	100		
2004	100		
2005	100		
2006	20	305	289
		321	289
		337	353
2007	23		
2008	96	353	337

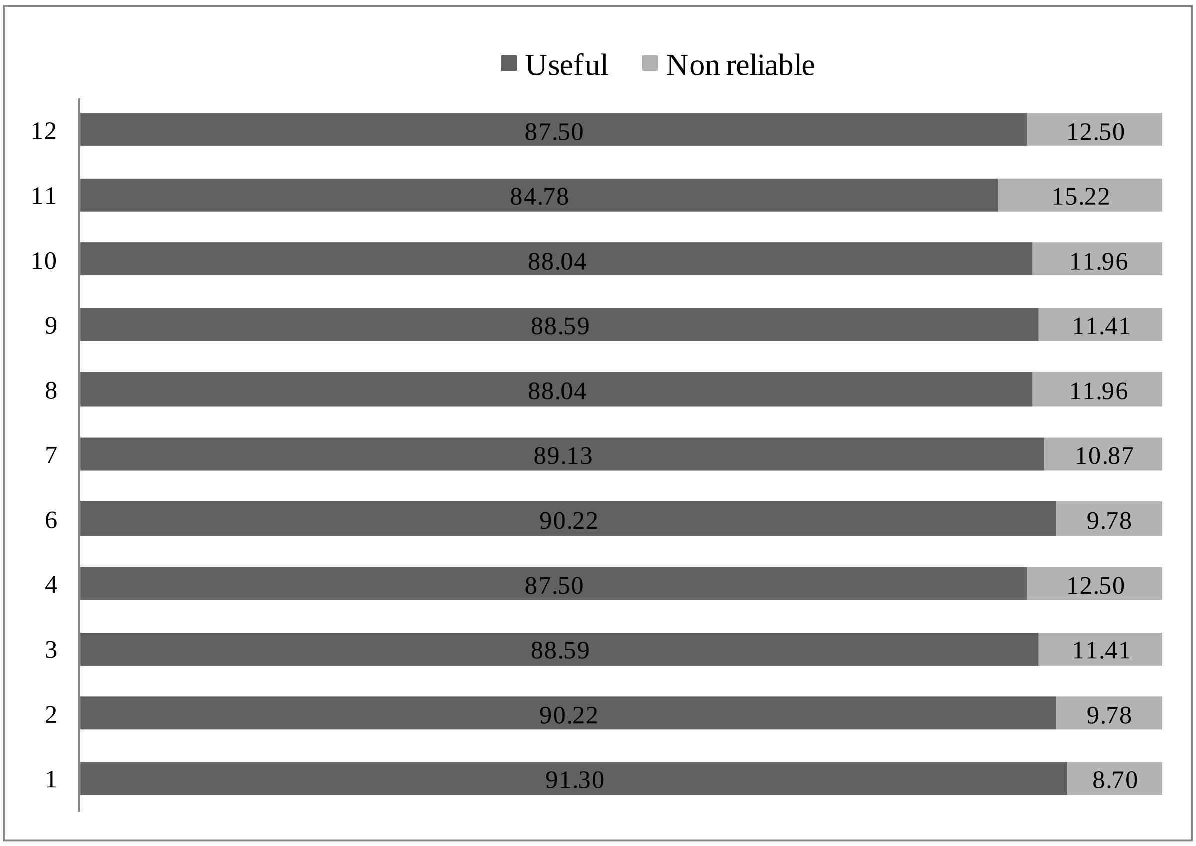
*Composite number is in Julian date.

Appendix D Coordinates of the central point in each of the modelled pixels of MOD13Q1

Pixel	Latitude	Longitude
1	27.8447079	86.7822528
2	27.8447079	86.7800877
3	27.8423496	86.7844951
4	27.8422336	86.7800877
5	27.8396046	86.7739793
6	27.8370288	86.7732363
7	27.8373768	86.7700612
8	27.8350716	86.7728492
9	27.8349846	86.7705658
10	27.8350281	86.7672602
11	27.8323098	86.7731971
12	27.8321793	86.7712834

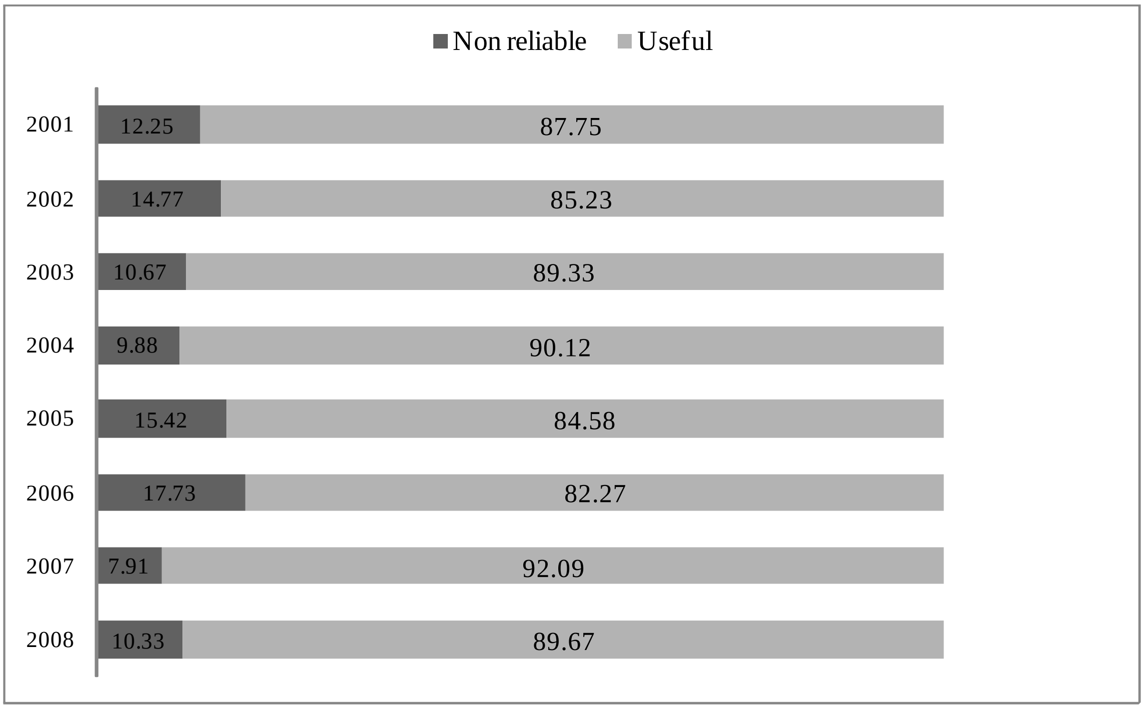
Appendix E. Summary of Pixel Reliability of MOD 13Q1 for each modelled pixel

Percentage of images with Pixel Reliability values classified as useful (values = 0 and 1) or non reliable (values 2, 3 or 255) for each analyzed pixel in the NDVI time series 2001-2008 (MOD13Q1)



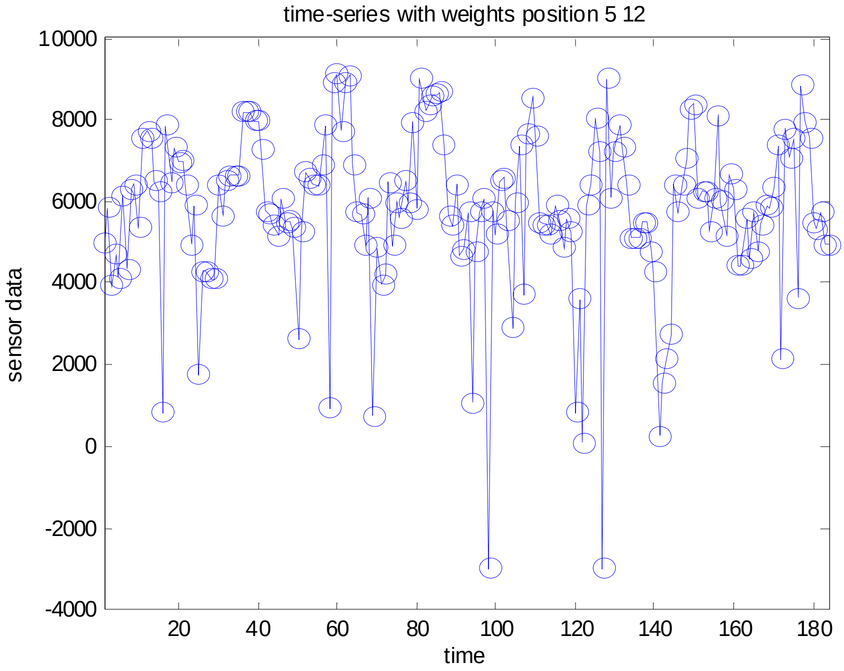
Appendix F. Summary of Pixel Reliability for each year in the time series MOD13Q1

Percentage of images with Pixel Reliability values classified as useful (values = 0 and 1) or non reliable (values 2, 3 or 255) for each year in the NDVI time series 2001-2008 (MOD13Q1) .



Appendix G. Example of assignment of weight and outlier identification by Timesatimage

Open circles represents initial weight assignment of each value in the time series



The red cross represent values determined as outlier in the time series, no weight is assigned to these values.